Dealing with Climatic Risk in Agricultural Research—A Case Study Modelling Maize in Semi-arid Kenya

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

Abstract

Rainfall variability is a dominant feature of crop production in semi-arid regions. Soil fertility is also a major constraint, and much of the research effort has been directed at agronomic or genetic factors that impact on either or both the supply and demand for water or nitrogen. This paper reports on the application of models to research aimed at improving maize productivity under the highly erratic rainfall regimes of semi-arid eastern Kenya. Steps undertaken to test and adapt the CERES-Maize model are described, and a revised version called CM-KEN is shown to provide a realistic description of the major issues of concern in maize production in the region, i.e. responses to plant population, planting time, location, nitrogen and water supply and the interactions between these factors.

The additional insight such a modelling approach provided in terms of the prospects for improving maize productivity in the region is examined. Current germplasm is shown to be well adapted to the limiting rainfall regimes of the region. The major gains in productivity are likely to come from improved management of soil fertility and soil surface management. Indications are that nitrogen fertilisers should have a place in more productive systems in the region.

Insights pertaining to the conduct of agronomic research in regions of high climatic risk are also examined. Between 10 and 20 seasons of fertiliser rate trials were shown to be necessary to identify an optimum N fertilisation rate with any degree of confidence (i.e. to reduce coefficients of variation of the optimum rate to 25 and 15% respectively). In contrast, application of a validated model to the historical weather data enabled 63 seasons to be 'sampled' and coefficients of variation of optimum N rate to be reduced to approximately 1%.

SEMI-ARID tropical regions dominate the agricultural production systems of Africa, India and northern Australia (Troll 1965). These regions are characterised by highly variable rainfall regimes in either or both the timing, amount, or within-season distribution (Monteith and Virmani 1991). Variability in other climatic factors such as temperatures and radiation is small and relatively unimportant in comparison with rainfall. One exception to this generalisation is the occurrence of high soil and air temperatures which can have significant impact on crop establishment and productivity for some crops in some regions (Herrero and Johnson 1980; McCown et al. 1985; Carberry and Abrecht 1991).

Coefficients of variation in total seasonal rainfall are in the order of 30–40% for locations with a single 'rainy' season (Jones, these Proceedings). Variability in seasonal rainfall is even larger in semi-arid regions of Kenya, which, because of their equatorial location receive two rainy seasons each year. At Katumani Research Station where much of the research reported in this paper was conducted, an average annual rainfall of 700 mm is split into two very short (approximately 3 months) and unreliable seasons averaging approximately 300 mm each (Keating et al. 1992). Coefficients of variation are in the 40 to 50% range for seasonal rainfall at Katumani.

Historically such bimodal rainfall regions have been better suited to pastoralism since the dry season is shorter than unimodal rainfall regimes. The two

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

† Kenya Agricultural Research Institute, PO Box 57811, Nairobi, Kenya

'dry seasons' in semi-arid eastern Kenya are, however, sufficiently pronounced that two very short-season crops have to be grown each year. Long-season pigeon pea is the exception to this, being sufficiently drought-tolerant and having a lifecycle that allows it to be grown across both rainy seasons and the intervening dry season (Nadar 1984b). In Kenya, these two seasons are referred to as the short rains (late October–December) and the long rains (April-June) but the relative extent and reliability of the two seasons varies from location to location. An examination of the rainfall record for the Katumani National Dryland Farming Research Centre in Machakos Kenya indicates the magnitude of the variability in seasonal rainfall (Fig. 1). It is obvious that mean seasonal rainfall provides little information on the nature of the rainfall regime that exists in such areas.

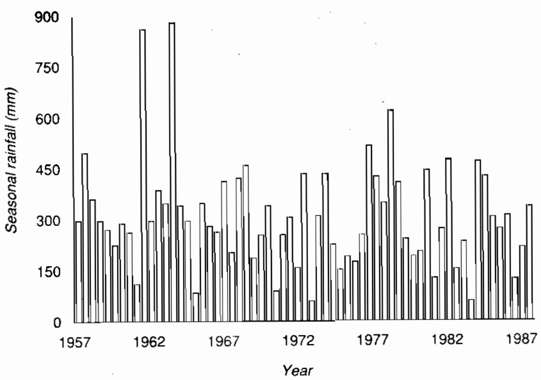

Figure 1. Seasonal rainfall at Katumani NDFRC, Machakos, Kenya. (Rainfall is accumulated over the period of growth of KCB maize as estimated by the CM-KEN Maize Model).

Agricultural research in areas such as this needs to confront the issue of climatic risk from both relevance and efficiency perspective. Firstly, there is a strong incentive for research to be relevant by identifying strategies that reduce the occurrence of low-yielding or failed crops associated with low rainfall years. Secondly, temporal variability in results from experimental work makes interpretation difficult and research time-consuming.

The KARI–ACIAR Dryland Farming Project sought strategies to raise maize productivity in the semi-arid lands of Machakos and Kitui Districts in eastern Kenya. The research work conducted within this project has been reported in detail elsewhere (Probert 1992). This paper reports on a modelling approach to make research more effective in addressing the constraints to agricultural production in regions of high climatic risk. It does this in terms of a case study involving research on production strategies for maize in semi-arid eastern Kenya. The paper aims to summarise this past research and reflect on the insights gained, in terms of both the likely impact of production strategies and technologies on the level and stability of maize production and, more generally, on effective approaches to research in semi-arid areas.

Maize Research in Semi-arid Kenya

There is a long history (approximately 40 years) of research into dryland farming practices in Kenya. The period from 1950 to 1985 was reviewed by Keating and co-workers (1992a). Issues such as planting times, plant populations, varietal selection, intercropping, fertiliser use, surface management, rotations and fallowing have all been examined and reported. The majority of these studies have sought to raise productivity by manipulating either or both the supplies of water and N and their demand by the crop.

Place for models

Models can be viewed as extended hypotheses put forward to describe the way in which a system will respond to various combinations of inputs. The crop production system, which was the focus in this case study, can be viewed as one which outputs crop and stover yields from soil and weather inputs. Genotypic characteristics and management decisions made by farmers modify system performance. Important non-linear interactions exist among genotypic, soil and management factors and in turn between these factors (singly and collectively) and weather. As discussed above, while radiation and temperature are important factors controlling crop growth and yield, it is interactions with rainfall that dominate the performance of semi-arid crop production systems.

Jones (these Proceedings) and Keating et al (1992) have argued that it is the complexity of these crop-soil-weather-management interactions and the variability associated with rainfall regimes in semi-arid regions that necessitates a modelling approach to the study of these systems.

Choosing an appropriate level of model

Models vary in scope and level of detail. Simple relationships between seasonal rainfall and crop yield have been in use for some time in Kenya (Glover 1957; Stewart and Faught 1984). These static models cannot capture the important interactions between rainfall distribution and crop development. Dynamic models, usually with a time-step of one day, are needed in water-limited environments where the pattern of rainfall is an important determinant of crop growth and yield.

The appropriate structure of a model also varies with the objectives for its use. Semi-arid eastern Kenya required a model that would predict maize yield in relation to the major soil and environmental factors and management options relevant to the region. This meant in particular that the model had to be able to simulate the demand by the crop for water and N, as influenced by management factors such as planting time, plant population, genotype characteristics. In addition the model needed to simulate the supply of water and N from the soil, in relation to weather, soil properties and management factors such as past cropping history and fertiliser application.

Developing a modelling capability

When this work commenced in 1985, the CERES-Maize model (Jones and Kiniry 1986) was the only model available that could deal with maize growth and development on a daily basis in relation to both water and nitrogen supply. A major international effort involving many tens of man-years of work had gone into the development of this model. Our strategy was thoroughly to evaluate this model in our region of interest, and where appropriate, make changes to model coefficients or structure to improve its predictive capability for the maize genotypes and environments of semi-arid Kenya. We started with version one of CERES-Maize, prior to its formal publication and release. Subsequent changes to the CERES crop, water and nitrogen models were either pre-empted or made after these versions were released.

CERES-Maize had been most strongly influenced by experimental data coming out of the better maize-growing environments of north America, and the major changes made related to the unique features of maize production in a low-input, semi-arid environment. These changes included addition of routines to simulate crop death and altered phenology under water and nitrogen stress and the modification of routines dealing with grain number estimation, leaf area development (Keating and Wafula 1992) and mineral nitrogen dynamics over fallow periods ('Birch' effect). Further details of these modifications are given in Keating et al. (1992a). A large number of operational enhancements were also made. These included a visual and interactive interface (Hargreaves and McCown 1988) and what is referred to as the 'response farming' routines. These latter routines enable rules to be established to effect planting, fertilisation and thinning in response to the timing and quantities of rainfall received. Such routines were essential for realistic analysis of maize production strategies utilising historical rainfall records. The modified model is referred to as CM-KEN (Ceres Maize in Kenya) to register the fact that it is different to the original CERES-Maize.

Model Performance

All data sets The model validation data set contained information from 159 crop/treatment combinations, with yields ranging 0–8000 kg/ha in response to variation in sowing date, water, nitrogen, plant population and climatic conditions. Full details of the model evaluation are given in Keating et al (1992b). The line of best fit between predicted and observed grain yield was close to the 1:1 line (slope (s.e.) = 0.94 (0.03) and intercept (s.e.) = 249 (103)) and coefficient of determination (r2) was 0.88, with a root mean squared deviation (RMSD) of 689 kg/ha.

Water × plant population interaction The model is capable of simulating the response of maize yield to plant population, under both favourable and limiting water regimes. The experimental data (Fig. 2a) show that when water was freely available (441 mm over the season), yields of the KCB cultivar increased from approximately 1500 to 7000 kg/ha as plant population was raised from 0.88 to 8.88 plants/m^2. When water was limiting (303 mm over the season), yields peaked at approximately 2800 kg/ha and declined as plant populations were raised above 3.7 plants m^2. This strong water × plant population interaction was accurately simulated (RMSD = 549 kg/ha) by CM-KEN for both the KCB (Fig. 2a) and DLC (not shown) cultivars.

Nitrogen × plant population interaction The model is also structured in such a way that the interaction between plant population and nitrogen supply can be simulated. 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. 2b). While the absolute precision of the predicted grain yields was not always as good, the model was clearly capable of predicting the general nature of the plant population by nitrogen supply interaction (RMSD = 582 kg/ha).

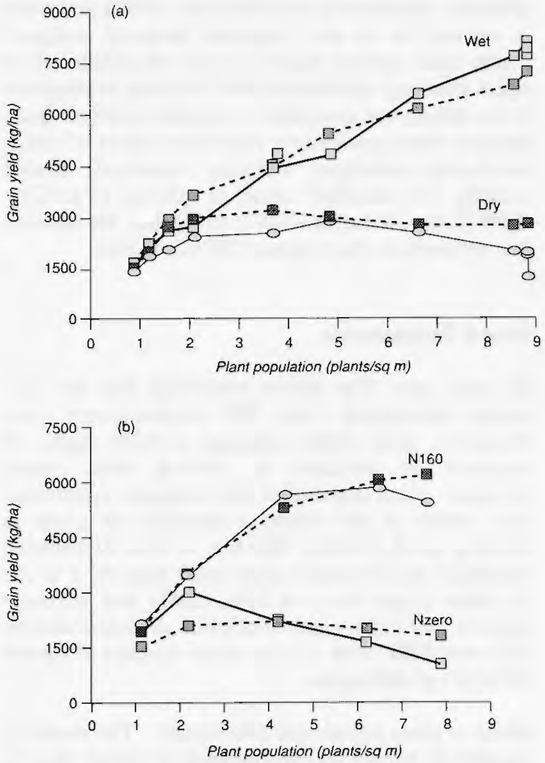

Figure 2. Observed (broken lines) and simulated (solid lines) yields of the KCB cultivar showing the interaction between plant population and (a) water regime and (b) nitrogen supply.

What New Insights for Farming in Semi-arid Eastern Kenya?

The availability of a model that dealt with the important genotypic, soil, management and environmental factors influencing maize growth meant that we could explore options for improving maize productivity without being constrained by the climatic variability that has plagued such studies in the past.

Plant populations, planting dates, genotype adaptation, losses due to runoff, nitrogen fertiliser management and tactical responses to weather patterns were all studied with the model over the historical rainfall record for Katumani (63 seasons from 1957). Analysis of the impact of single factors and the interaction between factors were conducted. Results of this work have been reported variously by Keating et al. (1991), Keating et al. (1992b), Keating et al. (1993), Wafula et al. (1992) and McCown and Keating (1992). The key findings can be summarised as follows.

- Currently available germplasm is well adapted to the rainfall patterns of the region. Gains from further selection for earlier flowering are likely only at the driest maize growing locations in the district (e.g. Agroecological Zone (AEZ) LM5) and even there, are likely to be small.
- The work confirms the widespread belief that planting as soon as possible at the start of the rainy season is desirable.
- Current plant population recommendations are generally appropriate (37 000 plants/ha = 3.7 plants/m^2) for the better maize growing locations in the districts (e.g. AEZ UM4). On shallow light-textured soils and in the drier zones (e.g. AEZ LM5), risks will be reduced with lower plant populations (1 to 2 plants/m^2).
- Productivity is very sensitive to losses of rainfall via runoff. Hence there are large benefits in crop yield available if practical methods of reducing runoff can be found. Such methods e.g. mulches must reduce runoff between the terrace banks which are a common feature on existing crop land.
- Nitrogen supply interacts strongly with plant population and lower plant populations (1 to 2 plants/m^2) reduce the risks in circumstances where N is likely to be strongly limiting.
- Some means of raising or maintaining soil fertility is a prerequisite to improving the productivity of these systems. Use of N fertilisers appears to be an economic proposition, although one that is not without significant risks.
- A nitrogen fertilisation and thinning strategy, conditional on the timing and extent of early season rainfall (i.e. 'Response Farming', Stewart and Faught 1984), does have a valid foundation in terms of the weather patterns and crop responses. The strategy has little impact on overall productivity compared to fixed strategies with similar levels of inputs, but does significantly reduce the risks of investing in fertilisers in seasons where no response will be obtained (Wafula et al. 1992).

From all these analyses together a picture emerges as to the current state of productivity in the region and the potential productivity if soil fertility is attended to and the most efficient use is made of the rain that does fall. This picture or more correctly, hypothesis, was presented by McCown and Keating (1992) as a four-step 'development pathway' (Table 1, Fig. 3).

Average maize yield (at Katumani over 1957–88) is predicted to increase from 970 kg/ha to 2740 kg/ha as inputs and associated management practices change from step 1 to step 4 (Fig. 3).

Table 1. Management inputs and parameters of the soil water balance for the simulation of four possible steps towards enhanced productivity (see Figure 4).

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

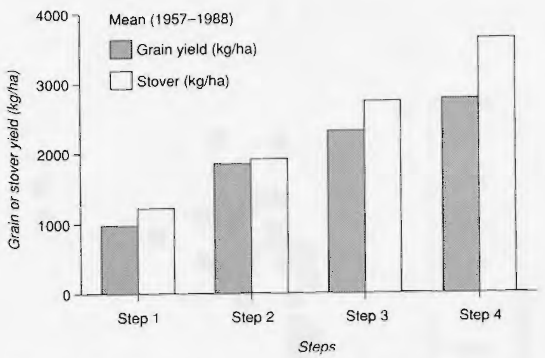

Figure 3. Mean maize yields simulated for Katumani weather over the 1957–88 period with increasing levels of inputs (details given in Table 1).

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

Step 2 involves small inputs of nitrogen fertiliser (10 kg N/ha), some increase in plant population and return of the 'additional' stover produced (i.e. over and above Step 1) to the soil surface.

Step 3 involves further increases in nitrogen fertiliser (20 kg N/ha), plant population and return of stover.

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

What New Insights for Research in Semi-arid Climates?

As a 10-year chapter of Australian and Kenyan interaction on dryland farming research draws to a close, it is appropriate to reflect on what insights the interaction has provided on the nature of agricultural research for semi-arid regions.

Addressing climatic risk — average effects

The overwhelming message for research planning and implementation from this study is that it is essential that some means of assessing the impact of climatic risk be incorporated into the research program. The model, when combined with the historical rainfall record, highlights the inadequacy of reaching conclusions from experiments conducted over short duration in semi-arid climates.

We have attempted to quantify this power of temporal extrapolation in an analysis of variability over time for response to N fertiliser. The analysis draws on the simulations reported in full by Keating et al. (1991). Briefly, the study involved KCB maize being simulated at Katumani at N rates between 0 and 160 kg N/ha over a period of 63 seasons from 1957 to 1988. Average yields and gross margins increased little beyond 40 kg N/ha (Fig. 4 a, b). Response to N fertiliser was highly variable (Fig. 4c) as has been shown experimentally in studies such as that reported by Nadar (1984a) (Jones these Proceedings). The majority of this variation can be related to seasonal rainfall amount (Fig. 4d), although the distribution of this rain in relation to crop development is also clearly important. From this analysis, optimum N rates, expressed in terms of gross margins, could be identified for each season (Fig. 5). These varied greatly over the duration of the rainfall record simulated.

If the temporal variability presented in Figure 4d is accepted as indicative of the extent of the variability in response to N fertiliser, an assessment can

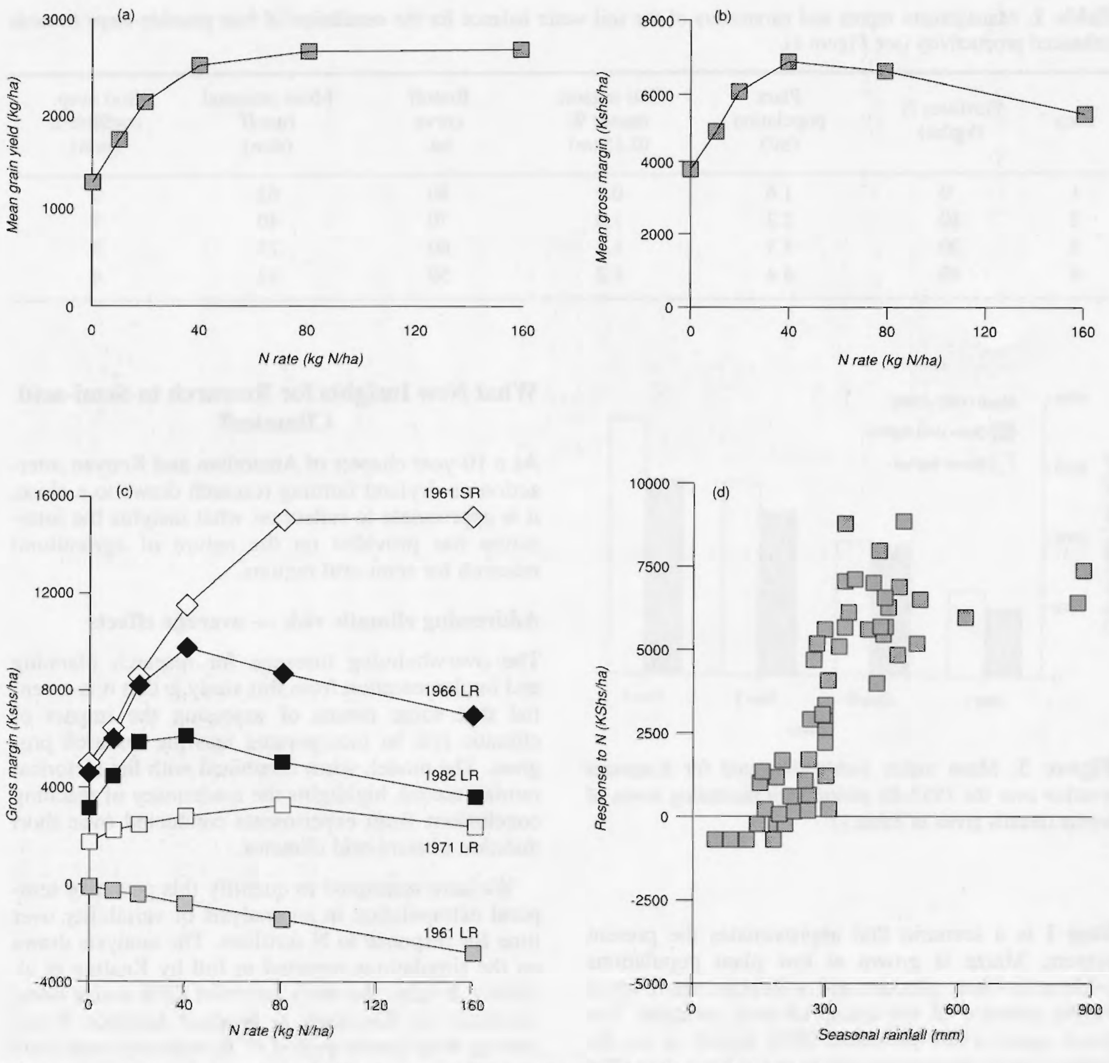

Figure 4. Effects of nitrogen fertiliser simulated at Katumani over the 1957 to 1988 period.
(a) Mean grain yield
(b) Mean gross margins
(c) Variation in response in gross margin for selected seasons (SR = short rains, LR = long rains)
(d) Relationship between additional gross margin resulting from the application of 40 kg N/ha and seasonal rainfall.

be made of the duration of experimentation needed to assess the expected returns from using N fertiliser in this environment. This has been done by sampling the population of optimum N rates depicted in Figure 5 and plotting the coefficient of variation in optimum N rate changes as a function of the number of seasons contained in each sample. Each sample was the mean of a number of seasons, ranging from 1 to 62 (sampled without replacement), and sampling was repeated 100 times. Coefficient of variation in optimum N rate decreased rapidly as the number of years sampled increased (Fig. 6). If a coefficient of variation of 15–25% was considered acceptable, and typical of much agricultural experimentation, this analysis reveals that 10–20 seasons of experimentation would be needed to identify an optimum N fertilisation rate with an acceptable degree of confidence.

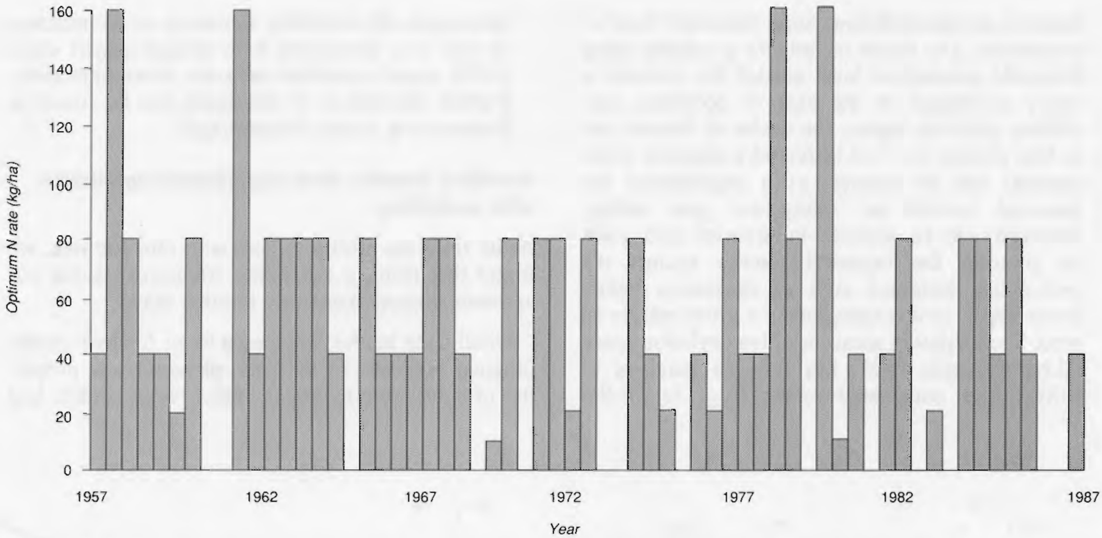

Figure 5. Optimum rate of N fertiliser (giving maximum gross margins) simulated at Katumani over 1957–88 period.

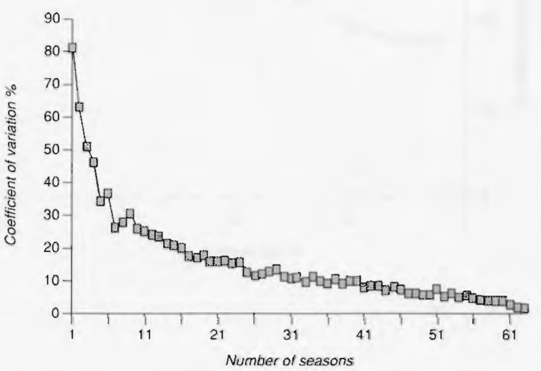

Figure 6. Reduction in coefficient of variation of optimum rate of N fertilisation with increasing number of seasons sampled. Seasonal variability in optimum N rate was derived from simulation of KCB maize at Katumani, 1957–88.

Addressing climatic risk—analysis of risks

This analysis has focused on the value of the model in assessing long-term average returns from a particular strategy. Equally important is the role the model plays in quantifying the risks associated with a particular practice.

Information on risk can be presented in a number of ways.

- The risk dimension of N fertiliser use is fully quantified in terms of cumulative distribution functions (Fig. 7a) which indicates the probability (y axis) of obtaining grain yields or gross margin less than the range (x axis) shown.
- One critical element of the complete risk profile shown in Figure 7a is the proportion of seasons when no positive returns are achieved from using nitrogen fertiliser. This was found to vary from 18 to 38% for the range of N rates shown in Figure 7b.
- If production is presented in terms of the long-term average gross margin (E), risk can be assessed in terms of the standard deviation of gross margin (SD) over the historical period simulated (Fig. 7c). Points to the upper left-hand side of such a figure maximise returns with minimum variability (or risk). A 2:1 rule of thumb has been suggested (Ryan 1984) as a first approximation to the attitudes of farmers on smallholdings to incurring added risk in conjunction with increased gross margin, i.e. such farmers would not be averse to using inputs or technologies provided they did not increase the standard deviation of the gross margin more than twice the increase in mean gross margin.
- Variability as measured by standard deviation can be a poor measure of the risks considered most important by farmers. In Figure 7d, standard deviation is replaced as a measure of risk by the

negative deviation below some threshold level of production. The desire of farmers to achieve some threshold production level needed for survival is easily envisaged. In the case of decisions concerning fertiliser inputs, the desire of farmers not to lose money (i.e. not to record a negative gross margin) can be viewed as a requirement for financial survival or 'safety-first' goal setting. Strategies can be assessed in terms of such goals by plotting the expected returns against the probability weighted sum of deviations below some target, in this case, below a gross margin of zero. Such a plot in mean-negative deviation space (E-ND) (Parton 1992) has obvious parallels to E-SD space considered earlier (Fig. 7c). E-SD space uses all variability in returns as an indicator of risk (i.e. deviations both up and down) while E-ND space considers only the down-side risks. Further discussion of this topic can be found in Probert et al. (these Proceedings).

Ancillary benefits from experimentation linked with modelling

Aside from the ability to deal with climatic risk, we found that using a modelling framework aided our agronomic experimentation in other ways.

Firstly, the model provided a focus for crop physiological research. In the past, physiological properties of crops were recorded, such as leaf number, leaf

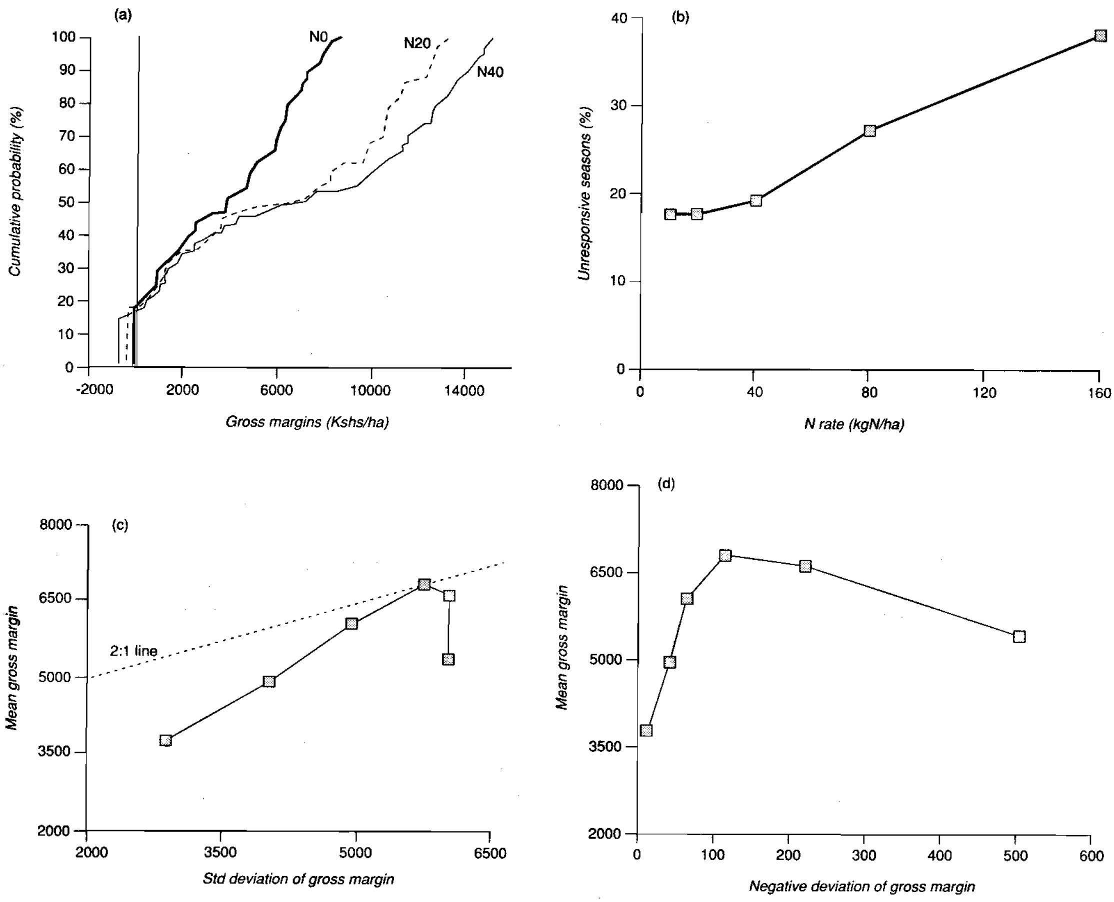

Figure 7. Measures of risk associated with nitrogen fertiliser usage.
(a) Cumulative distribution functions for a range of N rates (b) Proportion of seasons when responses are not achieved (c) Mean returns versus standard deviation of returns for a range of N rates as indicated in Figure 7(b)
(d) Mean returns versus probability weighted sum of negative gross margin for a range of N rates as indicated in Figure 7(b).

area, phenology and grain number, but researchers had little means to put such time-consuming measurements to use. Within a modelling context, such measurements serve the essential purpose of validating the accuracy of model components.

Secondly, the modelling approach promoted integration of the components of the agronomic research program. Agronomy research had been structured into components such as 'plant populations', 'fertilisers', 'intercropping' and 'agroclimatology'. There were also divisions between research station-based programs and on-farm programs. For the modelling studies, we quickly found ourselves doing experiments, both on-station and on-farm, examining the interactions between plant population, nitrogen fertiliser and weather, as influenced by planting date and water supply. Such experiments cut across the established divisions within the agronomic research program and thus promoted the need for a 'systems' view of agronomic strategies.

Thirdly, the desire to model experiments highlights the need for quality weather data and relevant soil properties. These forms of data tend to be not well recorded in agronomic research anywhere, be it Australia or Africa. While weather data are frequently recorded, because few persons use it, little attention is paid to their quality. Incorrect calibration of radiation recording instruments has been a commonly encountered problem in our work in both Australia and Kenya. Likewise, weather data tend to be sent to some central meteorological office, and rarely will researchers working in a particular environment have access to either the current or long-term weather data in a digital form. Modelling forces agronomic researchers to take a vital interest in quality weather data. The situation is often worse on characterisation of soil properties in agronomic experimentation. While a pedological classification may sometimes be available, few researchers measure soil properties that control water and nitrogen supply, even though such information might be essential to the interpretation of experimental results. When agronomic experimentation is conducted in a modelling context, the motivation for collecting such vital soil information is increased.

Obstacles to the Development of a Modelling Capability

This paper emphasises the benefits to be gained from coupling agronomic experimentation with a modelling framework. While we see this step as the only way forward in risky climates, we do not want to convey the impression that it is straight-forward and without its own difficulties.

Need for trained teams

Effective use of modelling in research for the semi-arid regions is held back by the unavailability of teams of scientists and experimentalists with skills in model development and application. While much progress has been made over the last 10 years, this still remains the major limitation in both Australia and Africa. The importance of training has been long recognised by groups promoting the use of modelling such as the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT 1988). That project has done much to expose crop researchers around the world to the role models might play in their research. This problem cannot be addressed only in terms of short-term training in how to use a particular model. A major change in perspective is needed, together with a significant investment in developing an understanding of the component crop and soil processes and in developing the skills required in software development, maintenance and model application.

Readers should not underestimate the challenges on this front. While training was considered an important issue in the KARI–ACIAR project in Kenya, this project ends after 10 years with only two people with well-developed skills in model development, testing and maintenance, and two additional scientists with skills in model application. Several are continuing their postgraduate training programs and none would consider themselves fully proficient in this area of work.

Need for better software

Another realisation from work with models in Kenya has been the need for better software design and software development and maintenance procedures, if models are to be a sustainable tool in agricultural research. Deficiencies of current software in this area compound the skills and training problems discussed above.

In the past, professional programmers have had limited input into the development of models used in crop research and the code available was both difficult to comprehend and error-prone. This problem was compounded by a tendency to 'patch-on' code to deal with new issues as they arise. We started our modelling in Kenya with an early version of CERES-Maize (version 1.0). Over the period 1985–92, this code developed in a pragmatic fashion, to meet the expanding needs of our research. New features to deal with weather-directed crop management, crop thinning, crop death and replanting options, tactical fertiliser management, mulch effects, surface residue decomposition, fallows, long-term analyses and interactive modelling were added. Inevitably, these enhancements became 'patches upon patches' and by as early as 1989 it had become obvious that a major redesign of the model was needed as we moved from what was essentially an individual crop model to a need for a cropping systems model with the soil as the central focus, and crops and residues 'coming and going' over time. This redesign has resulted in APSIM (Agricultural Production Systems Simulator) which is discussed in full by Carberry (these Proceedings).

References

Carberry, P.S. and Abrecht, D.G. 1991. Tailoring crop models to the semi-arid tropics. In: Muchow R C and Bellamy J.A. eds, Climatic Risk in Crop Production–Models and Management for the Semi-arid Tropics and Subtropics. CAB International, Wallingford, 157–182.

Glover, J. 1957. The relationship between total seasonal rainfall and yield of maize in the Kenyan highlands. Journal of Agricultural Science, 49, 285–290.

Hargreaves, J.N.G. and McCown, R.L. 1988. V/I CERES Maize. A visual/interactive version of CERES-Maize. CSIRO Tropical Agronomy Tech. Mem. No. 62. Published by CSIRO, Division of Tropical Crops and Pastures, Brisbane, Australia.

Herrero, M.P. and Johnson, R.R. 1980. High temperature stress and pollen viability in maize. Crop Science, 20, 796–800.

IBSNAT 1988. Experimental Design and Data Collection procedures for IBSNAT : Minimum Data Set for Systems Analysis and Crop Simulation, 3rd edn., Technical report 1, Dept. of Agronomy and Soil Science, University of Hawaii, Honolulu.

Jaetzold, R. and Schmidt, H. 1983. Farm Management Handbook of Kenya. Natural conditions and farm management information. Part C, East Kenya. Ministry of Agriculture, Kenya.

Jones, C.A. and Kiniry, J.R. 1986. CERES-Maize. A Simulation Model of Maize Growth and Development. Texas A&M University Press, College Station, 194 p.

Keating, B.A., Godwin, D.G. and Watiki, J.M. 1991. Optimising nitrogen inputs in response to climatic risk. In: Muchow R.C. and Bellamy J.A. eds, Climatic Risk in Crop Production–Models and Management for the Semi-arid Tropics and Subtropics. CAB International, Wallingford, 329–357.

Keating, B.A. and Wafula, B.M. 1992. Modelling the fully expanded area of maize leaves. Field Crops Research , 29, 16–25.

Keating B.A., Siambi, M.N. and Wafula, B.M. 1992. The impact of climatic variability on cropping research in semi-arid Kenya between 1955 and 1985. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 16–25.

Keating, B.A., Wafula, B.M. and Waitiki, J.M. 1992a. Development of a modelling capability for maize in semi-arid eastern Kenya. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No 41, pp 26–33.

—1992b. Exploring strategies for increased productivity — the case for maize in semi-arid eastern Kenya. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 90–100.

Keating, B.A., McCown, R.L. and Wafula, B.M. 1993. Adjustment of nitrogen inputs in response to a seasonal forecast in a region of high climatic risk. In: Penning de Vries F.W.T., Teng, P. and Metselaar, K eds, Systems Approaches for Agricultural Development, Kuler Academic Publishers, Dordrecht., 233–252.

McCown, R.L., Jones, R.K. and Peake, D.C.I. 1985. Evaluation of a no-till, tropical legume ley-farming strategy. In: Muchow R.C. ed., Agro-research for the Semi-arid Tropics : North-west Australia. University of Queensland Press, St Lucia, 450–469.

McCown, R.L. and Keating, B.A. 1992. Looking forward: Finding a path for sustainable development. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 126–134.

Monteith, J.L. and Virmani, S.M. 1991. Quantifying climatic risk in the semi-arid tropics : ICRISAT experience. In: Muchow R.C. and Bellamy J.A. eds, Climatic Risk in Crop Production–Models and Management for the Semi-arid Tropics and Subtropics. CAB International, Wallingford, 183–204

Nadar, H.M. 1984a. Maize response to row spacings and population densities. East African Agriculture and Forestry Journal, 44, 157–165.

—1984b. Intercropping under varying rainfall conditions. III. Maize/Pigeon pea.. East African Agriculture and Forestry Journal, 44, 182–188.

Parton, K.A. 1992. Socioeconomic modelling of decision making with respect to choice of technology by resource-poor farmers. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 110–118.

Probert, M.E., ed., 1992. A Search for Strategies for Sustainable Dryland Cropping in Semi-arid Eastern Kenya. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 138p.

Ryan, J.G. 1984. Efficiency and equity considerations in the design of agricultural technology in developing countries. Australian Journal Agricultural Economics 28, 109–135.

Stewart, J.I. and Faught, W. A. 1984. Response farming of maize and beans at Katumani, Machakos District, Kenya: recommendations, yield expectations, and economic benefits. East African Agricultural and Forestry Journal, 44: 29–51.

Troll, C. 1965. Seasonal climates of the earth. In: Rodenwaldt E. and Jusatz H.J. eds, World Maps of Climatology. Springer-Verlag, Berlin, 2–25.

Wafula, B.M., McCown, R.L. and Keating, B.A. 1992. Prospects for improving maize productivity through response farming. Proceedings of Dryland Farming Symposium, Nairobi, 10–11 December 1990, ACIAR Proceedings No. 41, 101–108.

Maize Root Profiles in Gleyic Sandy Soils as Influenced by Ridging and Ploughing in Zimbabwe

H. Vogel*

Abstract

Little information is available in Zimbabwe on the response of maize (*Zea mays* L.) plants to their root environment in poorly draining sandy soils. Since a large proportion of maize in Zimbabwe is grown on land frequently subject to waterlogging, a study of maize root profiles under field conditions was carried out during the 1992–93 rainfall/growing season. The prime objective of this field study was to characterise the distribution and to quantify the length of maize roots in gleyic sandy soils under a ridge till-plant system compared to conventional mouldboard ploughing. Concomitant plant analyses and monitoring of soil water contact provided further information on plant–soil interactions.

Although the study was limited in scope, the relationship between tillage, certain soil physical factors and rooting by maize plants could be fairly well defined. The results confirmed that ridging increases soil rooting volume and thus root length per unit volume of the soil resulting in significantly higher yields (6.6 t/ha compared with 5.1 t/ha).

GLEYIC sandy soils are widely distributed in the highlands (1200 to 2100 m a.s.l.) of subhumid (approximately 800–1000 mm/year) northern Zimbabwe where the regoliths are underlain by undulating granitic bedrock at shallow depth (Thompson and Purves 1978). Their particle size distribution ranges from loamy sand (FAO 1988) in the topsoil to sandy loam in the subsoil weathering zone and they are generally highly consolidated and compact (Vogel 1992). They are also acid in reaction (pH 4.4-5.0 in 0.01M $CaCl_2$) and low in both organic carbon (< 0.5% in the 0-200 mm layer) and exchangeable cations (e.g. 0.1K, 2.0 Ca, 0.5 Mg as $cmol^+ kg^{-1}$). The seasonally fluctuating shallow water-table, stone lines, termite activity and tillage also cause strong vertical and horizontal soil variations. The resultant heterogenous soil environment created by these natural soil formation processes and by cultivation greatly affects maize root growth and yields. The two most common problems associated with growing crops in such compacted soils are poor aeration and insufficient root length (Stirzaker and White 1991).

* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Conservation Tillage Project, PO Box BW 415, Borrowdale, Harare, Zimbabwe

Four years (1988-89 to 1991-92) of tillage trials showed that a system called no-till tied ridging (Elwell and Norton 1988) successfully addressed the problems of waterlogging and compaction best by providing additional and less densely packed rooting volume above the original topsoil (Vogel 1993; Table 1). It was also observed, however, that during prolonged dry weather early in the season the artificial heaping-up of soil raised topsoil temperatures to above 35°C and generated wide daily temperature fluctuations of more than 15°C in the elevated ridges between 0600h and 1400h (Vogel 1994b); both of which are detrimental to maize establishment.

In this study, carried out at the onset of tasseling of maize during the 1992-93 growing season, the objective was to describe quantitatively the distribution of roots and plant nutrients within the profile of ridged and ploughed soil.

Methods and Materials

The study site is located at Domboshawa Training Centre (latitude 17°35'S, longitude 31°10'E, altitude 1560 m a.s.l.) in northern Zimbabwe, 30 km north of Harare.

Horizontal and vertical root mapping (Logsdon and Allmaras 1991; MacRobert et al. 1991) were employed to study root profiles of maize that had been planted on 24 November 1992 in both permanently ridged and annually ploughed soil. Measurements were made 50 to 52 days after planting (DAP) at the beginning of tasseling (13 and 15 January 1993), in ongoing, long-term tillage trials where maize is grown in monoculture. Sampling at tasseling is considered the best time to obtain maximum maize root length densities (Mengel and Barber 1974).

The annual mouldboard ploughing treatment (MB) used is the conventionally practised tillage technique of Zimbabwe's smallholder farming sector. Ideally, ploughing is to the recommended depth of 230 mm (Grant et al. 1979) employing a single-furrow ox-drawn mouldboard plough. The no-till tied ridging (TR) treatment is a conservation tillage technique promoted by Zimbabwe's agricultural extension service. During the first year, the land is also ploughed to the recommended depth of 230 mm, and cross-slope crop ridges of not less than 250 mm unconsolidated height are then constructed. The ridges are not ploughed out after the first year but are permanently maintained to minimise draught power and loss of organic carbon. Surface runoff is controlled by laying out the ridges at a 0.4 to 1% gradient and by constructing smaller crossties at 1-m intervals along the furrows.

At the time the trials commenced, treatment plots were arranged in seven completely randomised blocks which are separated by contour ridges. However, prior to the 1991-92 growing season, one ridged and one ploughed plot of approximately 800 m^2 gross area each were added to two blocks for extra studies, i.e. a total of four new plots. One of the two blocks was situated in an upper catenal position, on a reasonably well-drained Areni-Gleyic Luvisol to Luvi-Gleyic Arenosol (FAO 1988). The other, located in a mid-catenal position, was characterised as poorly drained Eutric Regosol to Gleyic Arenosol with stone lines at shallow depth.

In each of the four plots, one soil pit was excavated according to the trench profile method (Böhm et al. 1977). The pits, dug across two crop rows, measured 1.8 m in width and 1.2 m in depth. The surface of the exposed soil profile wall was first smoothed with a putty knife and subsequently approximately 5 mm of soil was brushed off the profile face with a soft paint brush to expose the maize roots. A 1.0 m × 1.2 m metal frame (MacRobert et al. 1991) was positioned over the cleared maize root profiles with the maize plants always situated in the centre of the frame top. This metal frame was interwoven with thin nylon twine to form a 50 mm × 50 mm grid pattern. Within each grid square, the position of each 5 mm length of root was noted as a dot on scaled paper. The number of dots per grid square were totalled for each 50 mm depth increment across 0.9 m width (crop row spacing = 0.9 m) and converted to root length density (cm/cm^3).

Soil mechanical impedance was measured at the time of root mapping using a hand-held penetrometer (Anderson et al. 1980). The soil water content at this time was at field capacity throughout the depth of recording (= 0.52 m) in both treatments. For root conservations made between 51 and 58 DAP, cone resistance as determined during the week of root observation (and the previous week, which in our case gave the same result) produced the highest correlation with relative root abundance (Vepraskas and Wagger 1989). Five readings were taken at 35 mm depth intervals in each of the four plots within the maize rows (i.e. through the top of the ridges). Bulk density was determined as the oven-dry (dried for 24h at 105 °C) weight of 2.5 × 105 mm^3 undisturbed core samples also taken in situ at field capacity.

Soil water content was recorded weekly. Over the top 0 to 100 mm of the soil it was measured gravimetrically and converted into volumetric values by field-determined bulk densities. For lower depth levels (150 mm to 1.4 m) a CPN 503DR neutron probe was used which had been calibrated separately for the 150 mm depth level (r^2 = 0.94) and the lower (starting at 300 mm) levels (r^2 = 0.96).

One uniform fertility treatment was applied. A basal compound fertiliser totalling 24N:18.5P:17.5 K:19.5S kg/ha was applied at planting followed by two top dressings of ammonium nitrate (NH4NO3) each of 34.5 kg N/ha in mid-December 1992 and two days prior to root excavation and soil sampling.

The two maize plants from each pit were taken for nutrient analyses after root mapping. Harvested maize grain, as collected across all replications, was weighted and corrected to a uniform moisture content of 12.5% for final yield analysis.

Results

It is recognised that the results of this study are time and site-specific and also that the number of only eight maize root profiles analysed is small. Nevertheless, as will be shown, the effects of ridging and ploughing on crop growth and root distribution were sufficiently different and consistent to make up for the lack of replications. Crop height and the number of leaves per plant on the ridged plots were greater than on the ploughed plots and reflected the large differences in the respective root distributions (Figs 1-4). These results were also in full agreement with previous findings from extensive root excavation exercises which had established maximum root penetration depth below ridges (Vogel 1993, 1994a).

Seasonal rainfall pattern

At Domboshawa the 1992–93 season produced a total rainfall of 791 mm. Unlike in previous seasons (Vogel 1993, 1994a), no early-season drought occurred after planting (24 November 1992) but instead rainfall was plentiful and evenly distributed (Fig. 5a). Between the time of planting and the root mapping exercise (13 to 15 January 1993), a total of 370 mm of rain was received.

Soil water

The effect of tillage on soil water content was statistically significant (at $P < 0.05$) up to 25 November 1992 (that is until one day after planting), but only down to the 750 mm depth level (600–925 mm soil horizon) which coincides with the observed maximal root penetration depth (Fig. 2). Ridges entered the season with a significantly lower soil water content (Fig. 5b) and also kept the rooted profile considerably drier than conventional tillage throughout the growing season (Fig. 5c).

Between 10 December 1992 and 13 January 1993, overcast weather conditions prevailed. For a period of 5 weeks, soil water levels in ploughed soil remained between field capacity (ranging from

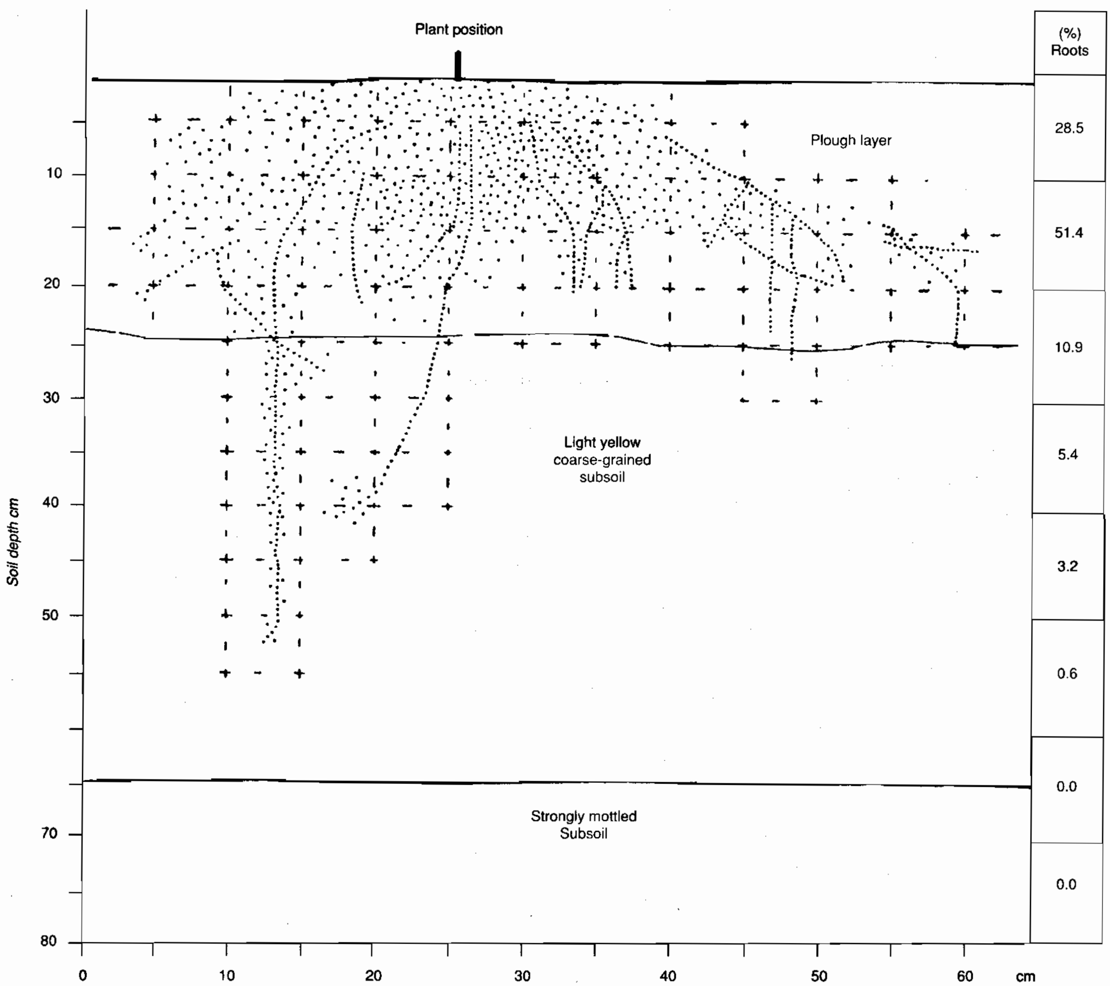

Figure 1. Maize root profile under mouldboard ploughing in reasonably-well drained Luvisol profile.

12.4% by vol. at 100-200 mm to 15.5% by volume at 450 mm depth) and approximately 20% by volume (saturation approximately 32% by volume) throughout the entire root zone. In contrast, soil water contents in the ridge tops (as measured between 0 and 100 mm and at 150 mm depth) always remained slightly below or at field capacity, and reached field capacity at 300 mm depth (14.0% by volume) during this time. Only at 450 mm depth below ridges were soil water contents recorded (15.3 to 18.9% by volume) that surpassed field capacity.

It is assumed that the prolonged wetness within 300 mm of the surface was the prime factor responsible for the stunted maize crop in ploughed fields compared to the tall crop on ridges at the time root mapping was carried out, i.e. 50 to 52 days after planting (DAP). Although it is generally agreed that a high soil water content per se has little meaning in terms of plant–water relations, it is well established that the primary effect of soil wetness within the root zone is attributable to its adverse effect on rhizosphere aeration which directly affects root growth and nutrient uptake (Van Schilfgaarde and Williamson 1965; Mackay and Barber 1985; Sojka 1985). Other research (Chaudhary et al. 1975; Hardjoamidjojo et al. 1982; Kanwar et al. 1988) also showed that maize yields are most reduced if soil wetness occurred during the vegetative stage, i.e. within 50 DAP, as was the case in 1992-93 at Domboshawa.

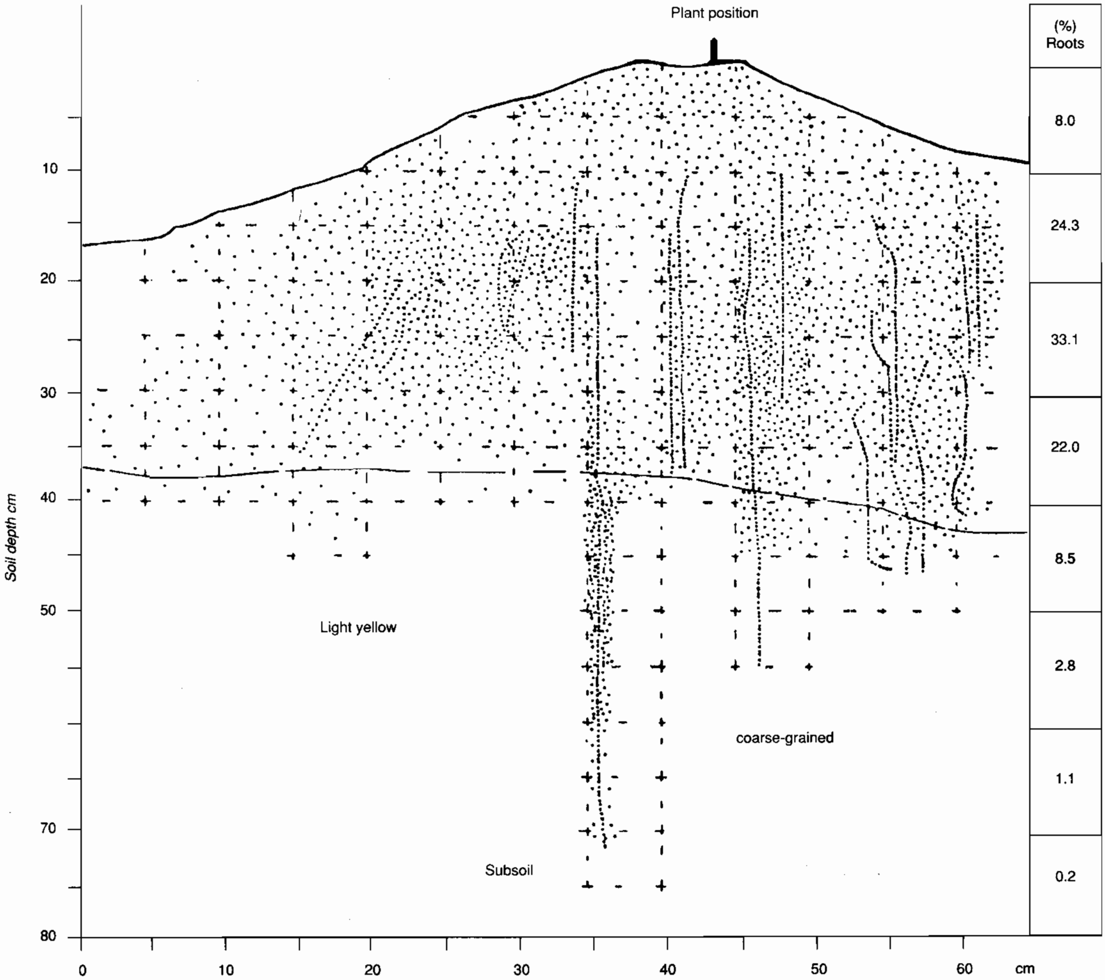

Figure 2. Maize root profile under tied ridging in reasonably-well drained Luvisol profile.

In spite of an air-filled porosity of 20–30% over the period of five weeks concerned, and although oxygen diffusion rate and redox potential data were not obtained in this study, observed and/or measured plant factors suggest aeration problems existed in the ploughed soil. Yellow leaves and a high concentration of 140 to 196 mg/kg of ferrous iron in the tissue of the maize plants taken from the ploughed fields at tasseling, as well as conspicuously less root growth in the 50-mm layer immediately above the topsoil-subsoil boundary (Figs 1 and 3), indicate the existence of transient waterlogged conditions and oxygen deficiency. In contrast, maize grown on ridges featured green leaves and the measured concentration of ferrous iron in its tissue only ranged from 118 to 126 mg/kg. There were no similar effects on the concentrations of other nutrients. The maize plants grown on ridges were significantly taller than those grown on the flat (Fig. 6). The assumption that aeration problems existed in the root zone is also supported by the results of a recent study of similarly marginal waterlogged soils in South Africia which showed that the oxygen (O2) to carbon dioxide (CO2) ratio of the soil air was improved in ridges compared to flat ground due to better internal drainage and thus unrestricted gas exchange between the atmosphere and the soil air (Myburgh and Moolman 1991). Other research also suggests that an 'aeration effect' on root growth may occur in sandy soils with up to 30% air-filled porosity (Eavis 1972, Warnaars and Eavis 1972).

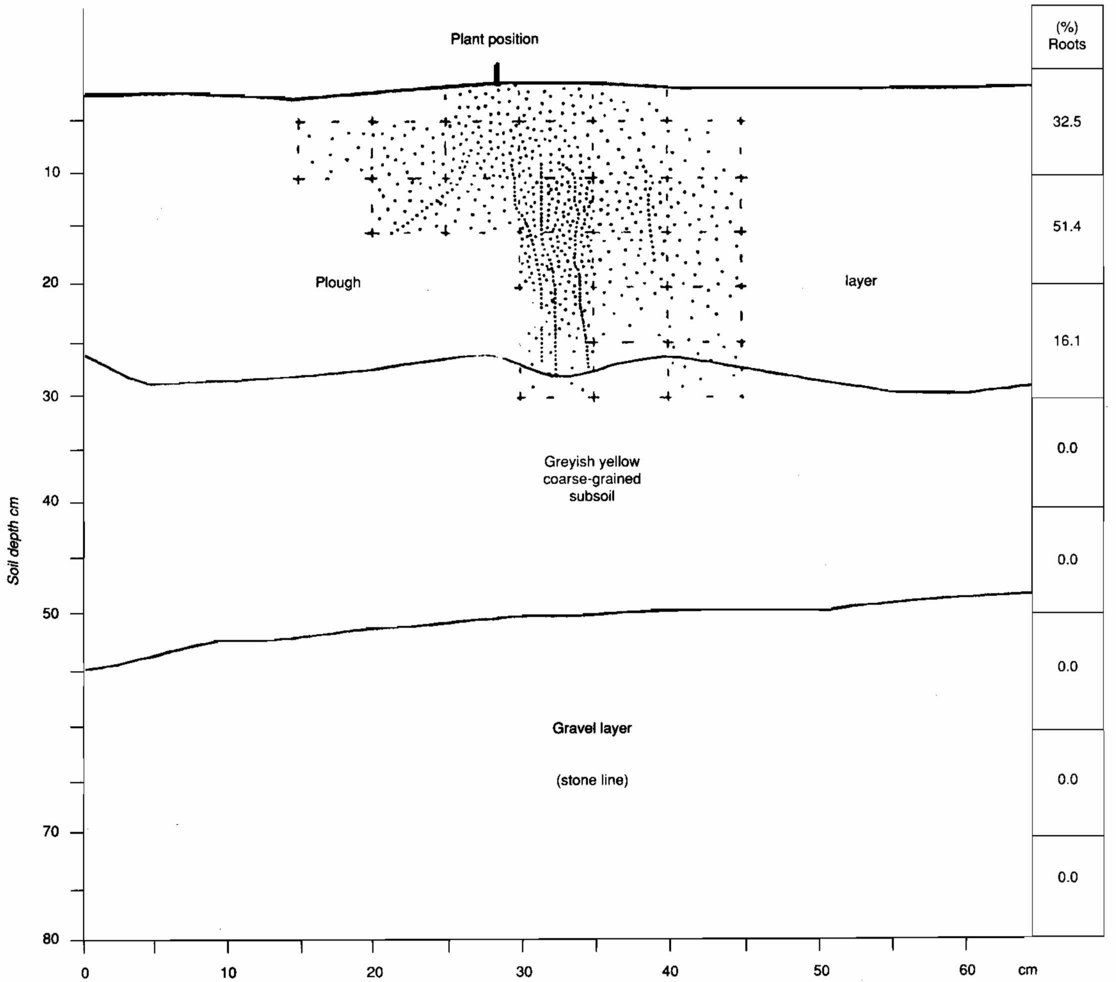

Figure 3. Maize root profile under mouldboard ploughing in poorly-drained Regosol profile.

Soil strength

It is assumed that besides poor aeration, high soil mechanical impedance played the prime role in limiting maize root growth in ploughed plots. Soil mechanical strength is assumed to be sufficient to stop bulk root growth at a critical pressure of 2000 kPa as determined by a cone penetrometer (Gill and Miller 1956, Taylor et al. 1966, Blanchar et al. 1978).). This threshold value was reached at approximately 270 mm depth under the ridges on the shallow Regosol, in both soil types under ploughing (Figs 7a,b) and at approximately 360 mm depth (Fig.7a) below the ridges on the deeper Luvisol. The penetrometry results thus fully confirm the mapping results (Figs1-4) which clearly show the vast bulk of roots confined to above these critical depths. They are also supportive of findings which suggest that a distinct reduction of root growth takes place when mechanical impedance and low oxygen concentrations occur together (Schumacher and Smucker 1981). Impeded roots were found to require more oxygen than unstressed roots which could accelerate the development of anoxic conditions. Furthermore, in field environments characterised by compact soil and frequent rains, oxygen diffusion (root elongation is more sensitive to the oxygen diffusion rate than to oxygen concentration) may drop to growth-terminating levels (< 33 m² s) within one day of heavy rainfall but may require one week thereafter to recover to growth-supportive levels (> 58 m² s) again

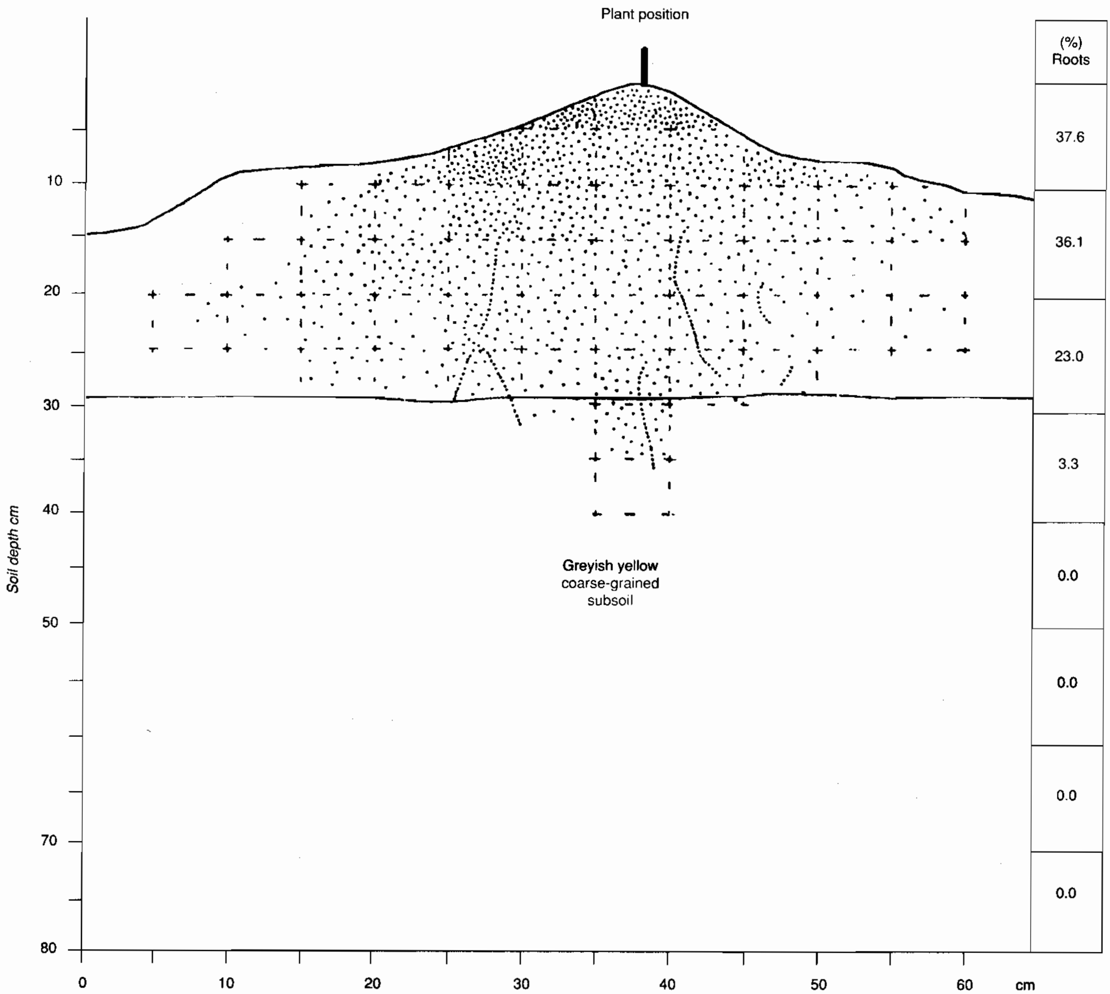

Figure 4. Maize root profile under tied ridging in poorly drained Regosol profile.

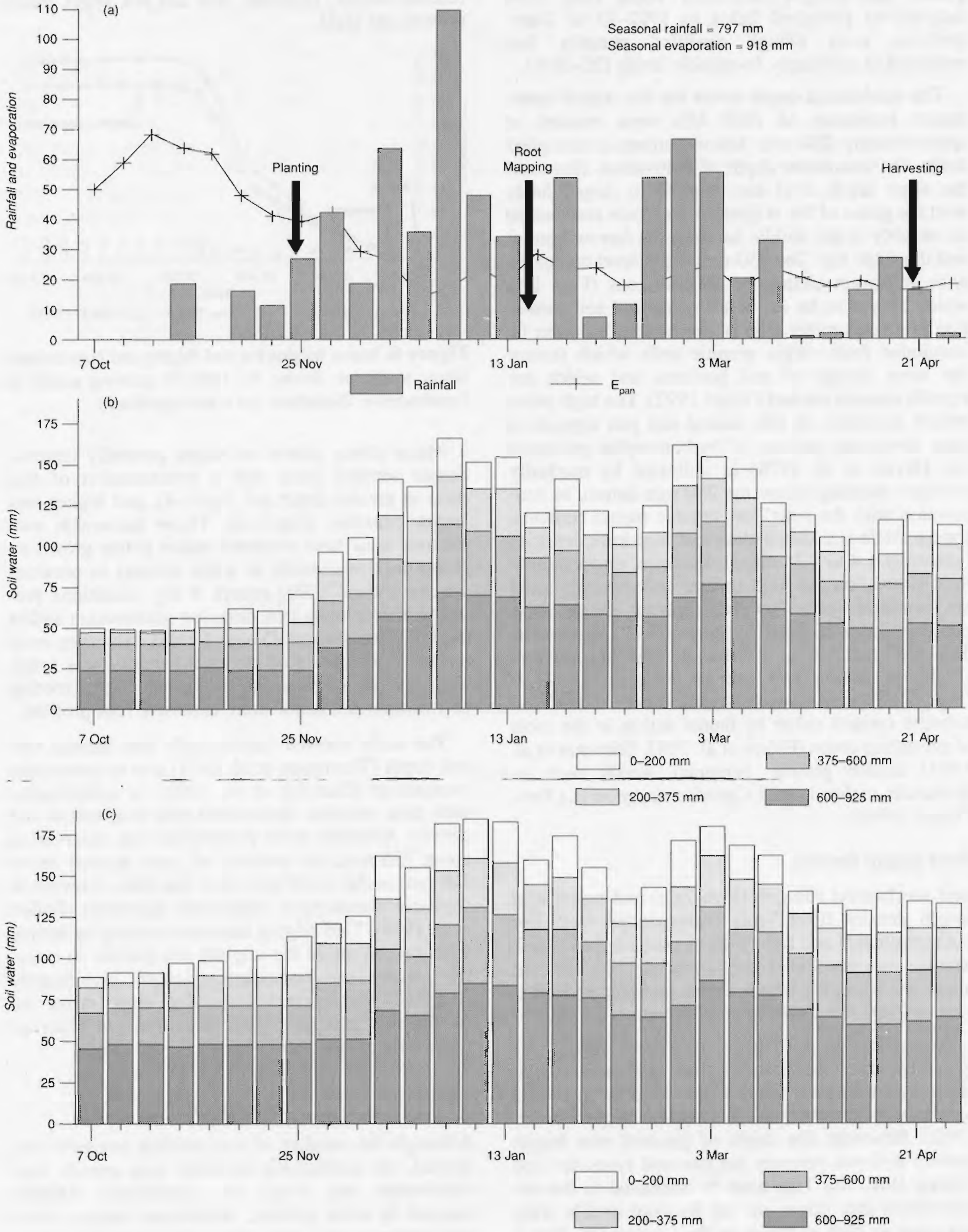

Figure 5. Moisture balance in the 1992–93 season: (a) total weekly rainfall and pan evaporation, and weekly measurements of soil water for the four depth layers, (b) under ridging (on the ridge), and (c) under conventional tillage.

(Allmaras and Logsdon 1990). Both findings suggested that oxygen deficiency could have been induced on ploughed fields in 1992–93 at Domboshawa even though air-filled porosity had remained at seemingly favourable levels (20–30%).

The established depth levels for the critical penetration resistance of 2000 kPa were reached at approximately 250 mm below surface in ploughed fields, the maximum depth of cultivation. However, the same depth level also applied to ridged fields with the plane of the original soil surface assumed to lie roughly in the middle between the furrow bottom and the ridge top. The 250-mm depth level coincided with an abrupt change of soil horizons (Figs 1-4) which appear to be the result of natural soil formation processes rather than of cultivation. This can be concluded from virgin granitic soils which feature the same change of soil horizons and which are equally densely packed (Vogel 1992). The high penetration resistance at this natural soil pan appears to have developed because of hydromorphic processes (cf. Davies et al. 1978) as indicated by markedly stronger mottling below the 250 mm datum, in conjunction with the soils' low organic matter contents, their particle size distribution and high bulk densities (generally 1.4 to 1.7 tonnes). However, under permanent cultivation the high natural soil strength could be increased further by the smearing and/or compressive action exerted by agricultural implements. The few roots able to penetrate the subsoil pan (Figs. 1–4) where soil strength exceeds 2000 kPa (Figs 7, b) may have followed zones of low soil strength created either by faunal action or the roots of preceding crops (Ehlers et al. 1983, Stirzaker et al. 1993) and/or prolific perennial weeds such as *Richardia scabra* L. and *Cynodon dactylon* (L) Pers. (Vogel 1994b).

Root length density

Soil mechanical strength (Figs 7a,b) and maize root length density (Figs 7c,d) corresponded well. For both treatments and soil types, maximum root length density was developed approximately 100-150 mm above the depth for which a cone penetrometer pressure of 2000 kPa could be established.

Maize root length density below the ridges was generally about 50% higher than in ploughed soil. Higher root length density for a ridge-till treatment has also been observed elsewhere (Kovar et al. 1992). However, the depth of greatest root length density differed between the two soil types for tied ridging (Fig. 7c). This must be attributed to the circumstance that ridges on the Regosol profile were not quite as high as those on the Luvisol (cf. Figs 1 and 3); consequently, the critical depth level corresponding to the restriction of root growth was reached earlier. However, this did not affect maize growth and yield.

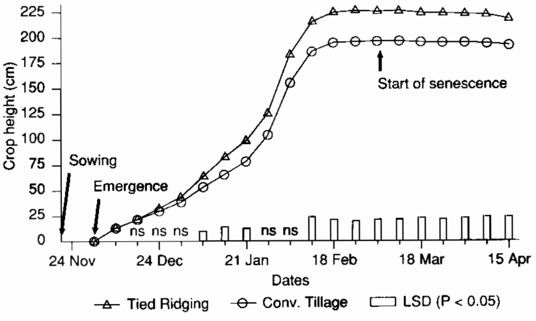

Figure 6. Maize heights for tied ridging and conventional tillage treatments during the 1992–93 growing season at Domboshawa, Zimbabwe. (ns = not significant).

Maize plants grown on ridges generally featured deeper seminal roots and a concentration of fine roots at greater depth (cf. Figs1–4), and higher root length densities (Figs7c,d). These favourable root features must have rendered maize plants grown on ridges less susceptible to water stresses in previous seasons (Vogel 1993) except if dry conditions prevailed after sowing thus delaying germination and/or inhibiting emergence (Vogel 1994a). However, once maize is established on ridges it becomes less sensitive to water stresses due to a much bigger rooting soil volume and hence more extensive root profiles.

The study showed convincingly that limited topsoil depth (Thompson et al. 1991) due to subsurface compaction (Oussible et al. 1992), in combination with poor aeration, determined root distribution and density. Although some penetration was observed to about 750 mm, the majority of roots resided above 300 mm in the soil (Figs1-4) as has been observed in similarly waterlogged sandy soils elsewhere (Follett et al. 1974). Tied ridging improved rooting by adding extra soil on top of the original soil profile. At maturity maize on tied-ridges yielded significantly ($P < 0.05$) more grain (6.6 t/ha) than maize on mouldboard ploughed plots (5.1 t/ha) as observed previously (Vogel 1993).

Conclusion

Although the number of root profiles analysed was limited, the relationship between crop growth, root distribution and tillage was conclusive. Ridging resulted in more prolific, denser and deeper maize root systems than ploughing; consequently, plants grown on ridges yielded significantly better. The

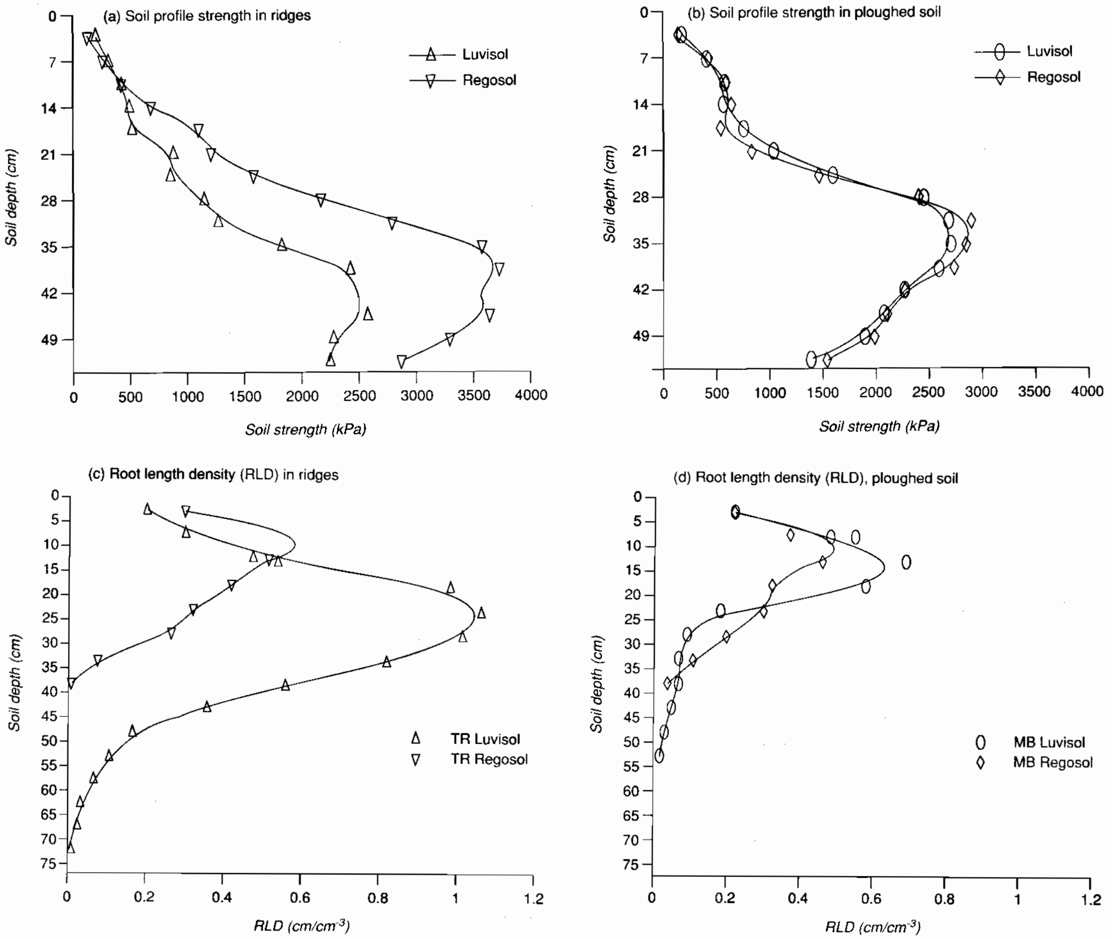

Figure 7. Soil profile strengths and root length densities in ridged and ploughed soils at tasselling in mid-January 1993 at Domboshawa, Zimbabwe.

observed root differences were ascribed to the additional topsoil layer created by the ridging which provided more favourable rooting conditions above physical restrictions of the subsoil. While the vast bulk of roots in ploughed fields were confined to the depth of cultivation (200–250 mm), ridging increased the vertical height of penetrable soil by at least 50–150 mm. Given the influence of ridge height on topsoil temperature and potential evaporation losses, future studies need to establish the optimal height and shape of ridges for the specific soil and climatic connditions prevailing in the study area. Knowledge of an optimal ridge height is also essential from a draught power point of view since high ridges require ploughing into extremely compact subsoil and/or gravel layers, a critical disadvantage in animal draught power.

Acknowledgments

I thank John MacRobert for his valuable advice and for kindly providing the metal frame for root mapping.

The plant analyses were done by the Chemistry and Soil Research Institute, Department of Research and Specialist Services (DR&SS) in Harare, and the soil analyses by the Zimbabwe Sugar Association Experiment Station in Chiredzi.

References

Allmaras, R.R. and Logsdon, S.D. 1990. Soil structural influences on the root zone and rhizosphere. In: Box, J.E. Jr. and Hammond, L.C. ed. Rhizosphere Dynamics. American Association for the Advancement of Science, Selected Symposium 113, 8-54.

Anderson, G., Pidgeon, J.D., Spencer, H.B. and Parks, R. 1980. A new hand-held recording penetrometer for soil studies. Soil Science Journal 31, 279-296.

Blanchar, R.W., Edmonds, C.R. and Bradford, J.M. 1978. Root growth in cores formed from fragipan and B2 horizons of Hobson soil. Soil Science Society American Journal 42, 437–440.

Böhm, W., Maduakor, H. and Taylor, H.M. 1977. Comparison of five methods for characterising soybean rooting density and development. Agronomy Journal. 69, 415-418.

Chaudhary, T.N., Bhatnagar, V.K. and Prihar, S.S. 1975. Corn Yield and Nutrient Uptake as Affected by Watertable Depth and Soil Submergence. Agronomy Journal 67, 745-749.

Davies, D.B., Spoor, G. and Godwin, R.J. 1978. Subsoiling. Leaflet 617, Ministry of Agriculture, Fisheries and Food (MAFF), Alnwick, Northumberland, United Kingdom, 10 p.

Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant Soil 36, 613–622.

Ehlers, W., Köpke, U., Hesse, F. and Böhm, W. 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil Tillage Research 3, 261–275.

Elwell, H.A. and Norton, A. 1988. No-till Tied Ridging. A Recommended Sustained Crop Production System. The Institute of Agricultural Engineering (IAE), Harare, Zimbabwe, 39 p.

FAO (1988). Soil map of the world. World Soil Resources Report No. 60, Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy, 119 p.

Follett, R.F., Allmaras, R.R. and Reichman, G.A. 1974. Distribution of corn roots in sandy soils with a declining water table. Agronomy Journal, 66: 288-292.

Gill, W.R. and Miller, R.D. 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. Soil Science Society America Proceedings 20, 154–157.

Grant, P.M., Meikle, G.J. and Mills, W.R. 1979. A comparison of plough types and depths of annual ploughing for maize monoculture with varied manuring. Rhodesian. Journal Agricultural Research, 17, 99-123.

Hardjoamidjojo, S., Skaggs, R.W. and Schwab, G.O. 1982. Corn yield response to excessive soil water conditions. Transactions of the ASAE 25, 922-927, 934.

Kanwar, R.S., Baker, J.L. and Mukhtar, S. 1988. Excessive soil water effects at various stages of development on the growth and yield of corn. Transactions of the ASAE 31, 133-141.

Kovar, J.L., Barber, S.A., Kladivko, E.J. and Griffith, D.R.1992. Characterisation of soil temperature, water content, and maize root distribution in two tillage systems. Soil-Tillage Research 24, 11-27.

Logsdon, S.D. and Allmaras, R.R. 1991. Maize and soybean root clustering as indicated by root mapping. Plant Soil 131, 169-176.

Mackay, A.D. and Barber, S.A. 1985. Soil moisture effects on root growth and phosphorus uptake by corn. Agronomy Journal 77, 519-523.

Mackay, A.D., Kladivko, E.J., Barber, S.A. and Griffith, D.R. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Science Society American Journal, 51, 970-974.

MacRobert, J.F., Wells, P.D. and Savage, M.J. 1991. A survey of farm wheat root profiles. Zimbabwe Science News 25, 83-86.

Mengel, D.B. and Barber, S.A., 1974. Development and distribution of the corn root system under field conditions. Agronomy Journal 66, 341-344.

Myburgh, P.A. and Moolman, J.H. 1991. Ridging — a soil preparation practice to improve aeration of vineyard soils. South African Journal Plant Soil 8, 189-193.

Oussible, M., Crookston, R.K. and Larson, W.E. 1992. Subsurface compaction reduces the root and shoot growth and grain yield of wheat. Agronomy Journal 84, 34-38.

Schepers, G. 1992.Water and the development of the maize plant. Farming World 18, 41–42.

Schumacher, T.E. and Smucker, A.J.M. 1981. Mechanical impedance effects on oxygen uptake and porosity of drybean roots. Agronomy Journal 73, 51-55.

Sojka, R.E. 1985. Soil oxygen effects on two determinate soybean isolines. Soil Science 140, 333-343.

Stirzaker, R. J., Passioura, J.B., Sutton, B.G. and Collis-George, N. 1993. Soil management for irrigated vegetable production. II. Possible causes for slow vegetative growth of lettuce associated with zero tillage. Australian Journal Agricultural Research 44, 831–844.

Stirzaker, R.J. and White, I. 1991. The effect of surface residues and biopores resulting from an in-situ mulch crop on tomato and lettuce production. In: Soil Tillage and Agricultural Sustainability. Proceedings of the International Soil Tillage Research Organisation 12th International Conference, Ibadan, Nigeria, 645–663.

Taylor, M.M., Robertson, G.M. and Parker, J.J. Jr. 1966. Soil strength-root penetration relations from medium-to coarse-textured soil materials. Soil Science 102, 18–22.

Thompson, A.L., Gantzer, C.J. and Anderson, S.H. 1991 Topsoil depth, fertility, water management, and weather influences on yield. Soil Science. Society America Journal 55, 1085-1091.

Thompson, J.G. and Purves, W.D. 1978. A Guide to the Soils of Rhodesia. Rhodesian Agricultural Journal Technical Handbook No. 3.

Van Schilfgaarde, J. and Williamson, R.E. 1965. Studies of crop response to drainage. I. Growth chambers. Transactions of the ASAE 8, 94-97.

Vepraskas, M.J. and Wagger, M.G. 1989. Cone index values diagnostic of where subsoiling can increase corn root growth. Soil Science Society of America Journal 53, 1499–1505.

Vogel, H. 1992. Morphological and hydrological characteristics of gleyic granitic soils and their potential for crop production. A case study from Zimbabwe. Soil Technology 5, 303-317.

Vogel, H. 1993. Tillage effects on maize yield, rooting depth and soil water content on sandy soils in Zimbabwe. Field Crops Research 33, 367-384.

Vogel, H. 1994a. The effect of tillage on topsoil temperature and strength in coarse-grained sands with special reference to a tied ridging system. Experimental Agriculture 30, 57–66.

—1944b. Weeds in single-crop conservation farming in Zimbabwe. Soil Tillage Research, (in press).

Warnaars, B.C. and Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth. II. Mechanical impedance, aeration and moisture availability as influenced by grain size distribution and moisture content in silica sands. Plant Soil 36, 623–634.

Agricultural Systems Research in Africa and Australia: Some Recent Developments in Methodology

R.L. McCown and P.G. Cox*

Abstract

Soil fertility depletion is a recurring, and increasingly urgent, theme both in sub-Saharan Africa and in Australia. It poses severe problems for a farming systems research approach that focuses on breaking constraints to production in a sequential and isolated fashion, and working with individual farmers. Additional approaches are required to evaluate the design of novel farming systems, and to change the attitudes and behaviour of groups.

When farming systems research (FSR) was getting started in Africa, Australian researchers moved down a different route towards the construction and use of crop models. These are now well developed and sufficiently reliable for use in operations research. But this activity, and the decision support products it spawns, is also increasingly seen by many as problematic and deficient.

In Australia, we are beginning to recognise that FSR and modelling are components of a wider systems approach. We shall need to bring all our system skills to bear if major problems like soil fertility depletion are to be ameliorated. But the eclectic approach we are developing is, we believe, the beginning of a reproducible and transferable research methodology which could be usefully applied more widely.

SOCIETY expects professional agricultural researchers to find out what good farming is, and to help farmers do it. But in most of Africa, and much of Australia, few farmers use the practices that researchers think necessary for efficient and sustained production. Why do we not see greater use of existing good farming methods? Is the discrepancy between good farming and much of actual farming due to a failure of researchers to appreciate sufficiently the realities which farmers face, or to our failure to help them change to something better? Is this discrepancy due to inadequate attention to technology design leading to the promotion of inappropriate technologies? Or to a failure to communicate well enough about the relative costs and benefits of alternative strategies?

In 1985, the Australian Centre for International Agricultural Research (ACIAR) hosted an international workshop 'Agricultural Systems Research for Developing Countries' (Remenyi 1985). At this meeting, these questions were addressed in the context of both eastern and southern Africa (Norman and Collinson 1985) and Australia (Remenyi and Coxhead 1985). While encouraging progress was reported, deficiencies in methodology for providing answers were obvious. The aim of this paper is to consider these generic questions and some recent developments in methodology used to answer them. We take as an example the decision to invest in soil fertility improvement in situations where soils are seriously depleted but where the economics of nutrient replacement is problematic because production is so often water-limited. This situation applies in many parts of Africa and Australia.

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

Soil Fertility in Sub-Saharan Africa

Probert and co-workers (these Proceedings) describe the serious problem of soil fertility depletion in a region of Kenya. In the 1970s, Ruthenberg highlighted the growing importance of the issue of soil fertility maintenance in farming systems of the African savanna zone, and predicted that soil degradation would become more general as pressure on land resources increased (Ruthenberg 1980).

Broekhuyse and Allen (1988) describe the destruction of the productive capacity of the Mossi plateau (Burkino Faso) by its inhabitants, and the social processes of overexploitation which apply to much of the savanna zone. Lynam (1978) has described a similar process in the Machakos and Kitui Districts of Kenya. The causes of overexploitation (high rates of rural population growth, shortage of suitable land for further expansion of cropping, and poverty which precludes replacement of soil nutrients at rates that will sustain productivity) already operate over much of Africa on scales, and to degrees, varying from worrying to catastrophic.

The problems of land degradation and low productivity are now so widespread in semi-arid Africa that it is easy to forget that this is not the natural state. Broekhuyse and Allen (1988) report that while 400 kg/ha is today considered a *good* grain sorghum yield on the Mossi Plateau, an ethnographic survey indicated that this is half the *normal* yield of former times. This decline has taken place over four generations — a rate that was perceptible within each generation, but not high enough to cause alarm.

The longer the delay before investing in soil fertility replacement, the greater the nutrient response and the higher the rate of return on the investment. Matlon (1987) refers to an FAO rule-of-thumb that adoption of fertiliser requires a 100% return on investment i.e. a 2:1 benefit–cost ratio. He reports a value of 350% for sorghum in areas of Burkino Faso in the early 1980s when the rate of fertiliser use was increasing. But as population increases, fallows shorten, soil fertility declines, and poverty deepens. While the potential response to a unit of nitrogen increases under these circumstances, the financial resources needed to purchase fertiliser progressively decline. These authors rule out fertiliser as a feasible innovation because it represents such a large, and increasing, proportion of the average annual income. The only action that might break the physical resource constraint is thus precluded by poverty.

Amelioration of soil fertility decline in sub-Saharan Africa will require enormous changes in education, public policy and administration. But the confusion that exists about the nature of the problem, and the availability of technical options, is puzzling. The technical constraints on any solution are clear.

1. Nitrogen and phosphorus are the elements in most short supply.
2. Most strategies for *avoiding* the constraint actually increase the efficiency of *depletion* e.g. better-adapted plants, increased water-use efficiency.
3. Animal manure can supply the required nutrients, but there is not nearly enough manure in cropping regions to prevent further decline.
4. Chemical fertiliser needs to be supplied, but in conjunction with manure to maintain sufficient organic matter levels and prevent acidification.
5. Poor management of high input systems in industrialised countries has created specific environmental problems. But this provides no grounds for protecting the fertility-impoverished environments of the tropics and subtropics of Africa and Australia from this remote risk.
6. Grain legumes do not provide a net increase in soil nitrogen, even when P is sufficient.
7. The conditions for successful legume ley pasture systems do not exist in Africa (e.g. affordable P fertiliser for pastures, good returns in animal enterprise from investment in sown pastures). In regions with most need, population pressures are too great for this level of cropping intensity.
8. Trees in semi-arid cropping systems are a mixed blessing. Some can provide useful amounts of nitrogen (e.g. leucaena alley cropping) and others recover nutrients at depths beyond the crop root zone. But they compete so strongly for water and nutrients that they are frequently detrimental.

Farming Systems Research in Africa

Farming Systems Research (FSR) emerged as a research approach in the late 1970s and underwent much of its development and testing in Africa. At the time of the ACIAR conference in Australia, Norman and Collinson (1985) could state that 'nowhere is increasing commitment [to FSR] more obvious than in the Eastern and Southern Africa region where we work'. Although Collinson's FSR schema has been re-used by numerous authors, we do so again because it depicts the approach so clearly and succinctly (Fig. 1, adapted from Anderson et al. 1985). The aim is efficient use of scarce resources for research, development and extension in delivering practical benefits to farmers. To Remenyi and Coxhead (1985), the key question in FSR is: why does this farmer farm as he/she does? In this paper, we highlight the other side of this question: why doesn't he/she do certain things that would be, apparently, in his/her interest? In FSR, these questions about technology design are explored using a step-wise process of *on-farm diagnosis; planning*, using an operational research approach; targeted *component research* on research stations when required; and *on-farm testing* of promising alternatives.

We can consider the merits and limitations of FSR by looking at the *diagnosis* and *planning* stages and the *scale* aspects of this approach in relation to the issue of soil fertility decline.

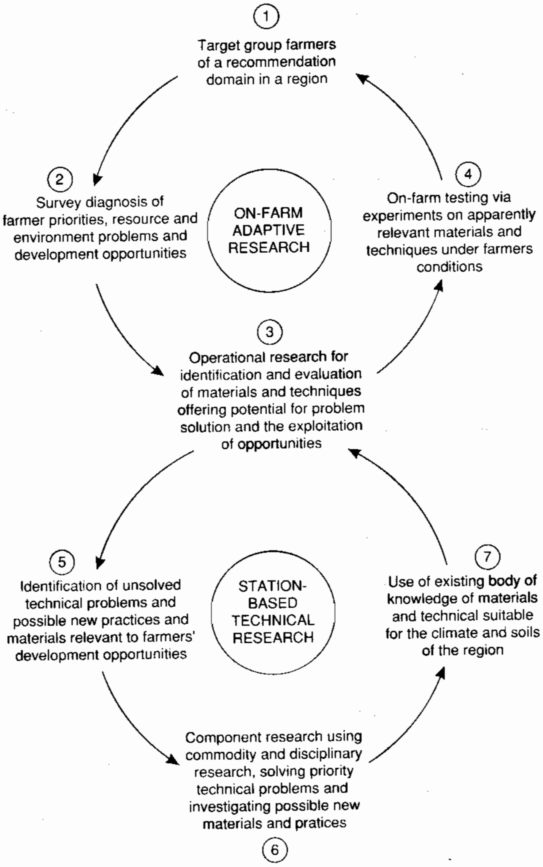

Figure 1. Schematic of Farming Systems Research methodology (Collinson 1982, modified by Anderson et al. 1985).

Diagnosis

On-farm measurement is central to the diagnosis of soil fertility decline. But measuring the status of soil nutrients such as nitrogen (N) and phosphorus (P) is made difficult and expensive by the heterogeneity of soil fertility on smallholdings due to, for example, non-uniform return of manure. Nor, in general, has experimentation on fertiliser application rates provided a reliable basis for management. Here the heterogeneity problem is compounded by the variable and unpredictable occurrence of other constraints, e.g. water deficits, pests, diseases and weed infestations, all of which result in a reduced response to added nutrients. Conclusions about the state of soil fertility in Africa based on a synthesis of large numbers of fertiliser response trials greatly underestimate the size of the problem.

While precise problem diagnosis is not easy, and perhaps not even feasible under such conditions, it is inescapable that farming cannot continue unless nutrients removed in crops, or lost in other ways, are replaced. Yet this is almost never achieved in contemporary smallholder agriculture. The common explanation is that farmers with very low incomes cannot afford to buy inputs.

Planning

At the earlier ACIAR workshop in Australia, Norman and Collinson (1985) offered two possible ways of dealing with a constraint in the farming system: relieve it, or avoid it by exploiting flexibility in the system. They observed that 'flexibility in management is enhanced when there are underutilised resources, while increasing productivity is vital to breaking constraints'. Later, Norman and Collinson state, 'if one looks at the success of FSR work to date, much of it can be attributed to exploitation of flexibility rather than breaking constraints'. And finally, 'we submit that breaking a constraint is a much more difficult problem for both researchers and farmers than the strategy of exploiting flexibility. However, major long-term increases in productivity have to come through breaking constraints'.

Seven years later, Waddington (1992) reported examples of successful on-farm experimentation by FSR teams. He observed that most examples could be regarded as 'fine tuning' of existing technologies in environments with some slack in resources. Where technologies did not already exist, and in regions with great pressure on resources, little success was experienced.

An indication that Norman and Collinson (1985) had not substantially engaged the issue of soil fertility maintenance is their statement that 'we believe that criteria used in developing improved strategies should reflect the felt needs of farming families, providing these are compatible with the needs of society (e.g. there is not a decline in soil fertility)'. This implies that an innovation with a negative effect on soil fertility would be exceptional. We think it is now clear that an innovation (such as a higher yielding cultivar) which exploits slackness in resources necessarily *accelerates* soil fertility depletion unless some of the increase in returns is invested in fertility inputs.

In the relatively favourable environments in which FSR has had its successes, relief of soil fertility constraints may be seen mainly as Norman and Collinson (1985) did, as necessary for 'major long-term increases in productivity'. However, where resources are under pressure, relief of soil fertility constraints is required to enable farming to continue to be viable as a means of sustaining low-income subsistence and not degenerate into the environmentally destructive, and ultimately self-destructive, activity of 'survival farming' (Broekhuyse and Allen 1988).

Scale

Broekhuyse and Allen (1988) distinguish the anglophone style of FSR and the francophone style, which has a more institutional, regional and long-term emphasis. They found the latter more useful when the problem was collectively destructive behaviour at the scale of landscapes by farmers each acting in his/her own best (short-term) interests. Changed behaviour did not occur unless the unit undertaking change was the village rather than the individual.

The failure of FSR to deal with issues of land degradation, such as soil fertility depletion, stems partly from its focus on the welfare of individual farmers, their perspective of their own needs, and of the choice of remedial actions within their control. While focus at this scale constitutes the strength of the FSR approach for many issues, other scales are important for the management of soil degradation.

On the Mossi Plateau, the francophone style of FSR, while casting the problem in a wider context, did not result in breaking the soil fertility constraint. The fundamental problem is a scarcity of a costly resource which is unaffordable by most farmers. In those parts of the world where sustainable agricultural systems are well developed, the means for preventing serious fertility depletion are well known and the cost of the necessary inputs is accepted (and acceptable). However, where circumstances force economically-rational farmers to farm in ways that are unsustainable and damaging to present and future society, there is a need for innovative policy initiatives. Soil erosion is a problem in political economy. Additional approaches are required (Biggs and Farrington 1993).

Systems Research in Australia

FSR has not been seen as appropriate to the R&D needs of Australian farmers. Scientists have assumed they knew their needs well enough, and that farmers could readily fit new R&D products into their systems. Systems research has mainly taken the form of economic modelling, simulation modelling and decision support systems (Remenyi 1985). But agricultural Research, Development and Extension (R,D&E) institutions in Australia increasingly recognise the value of a richer systems approach to meet the challenges presented by the complexities, uncertainties and conflicts in modern agricultural production. People-oriented systems approaches now exist alongside the 'hard' systems approaches. These have drawn heavily on Soft Systems Methodology (Checkland 1981; Checkland and Scholes 1990).

Another development has been to combine simulation modelling of agricultural production systems with the client-orientation of FSR (McCown 1991). The establishment of the Agricultural Production Systems Research Unit (APSRU) by the CSIRO Division of Tropical Crops and Pastures and the Queensland Department of Primary Industries is an example of this. APSRU is a team of 17 professionals with a charter to facilitate collaboration and convergence of R, D&E effort for dryland agricultural production systems.

APSRU's primary mandate region is the subtropical grain-growing areas of eastern Australia. Although it is more variable than for the cropping regions of Africa, the climate of this region of Australia is similar to that of southern Africa. In spite of high yield variability caused by unreliable rainfall, the region developed into a major producer of both winter and summer grains and the most important source of prime hard wheat. Rain rarely allows double cropping. Rain stored during a previous clean fallow provides much of the water for most crops. Grazing of cattle or sheep is also important on most grain farms, but ley pastures are rare. In recent years, dryland cotton has become an important crop.

Total nitrogen in the pristine black cracking clay soils was originally high (> 0.3% on some soils). In some areas, cropping had been practised without nitrogen fertilisation for 50-80 years before crop decline became evident. R,D&E during this period focused primarily on relieving biological and physical constraints to the exploitation of the rich soil resource through new crops and cultivars, and improved water conservation and utilisation.

But it has become clear, with a dramatic decline in protein content of wheat and consequent loss in financial returns, that the 'honeymoon' is over. Soil nitrogen, and particularly the economics of nitrogen supply, are amongst the most important issues in this farming system. Soil erosion, especially during summer fallows when rainfall intensities are high and decomposition rates of surface residues are high, exacerbates the problem.

Technological components

Figure 2 depicts four technological components which are widely held by professional agriculturalists to be key ingredients of profitable and sustainable cropping in this region now and increasingly in the future: opportunity cropping, conservation tillage, fertiliser and purposeful crop sequence. Each of these is important in its own right but they also interact in a complex way to influence the supply of water and N, and their use by crops.

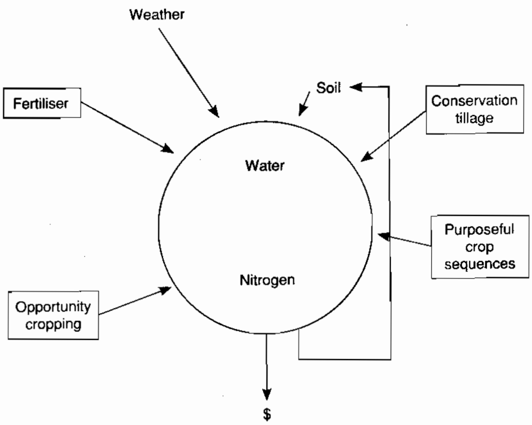

Figure 2. Technological components that contribute to improved strategies for managing scarce soil water and nitrogen supplies in subtropical eastern Australia.

Opportunity cropping is the strategy of planting whenever there is adequate soil water for the establishment and growth of a crop. This is a flexible response to the weak seasonality of rainfall. This strategy has been promoted as a soil conservation measure because it maximises crop cover of soil. Even though average crop yields are reduced vis-a-vis regular winter or summer cropping and fallowing, more crops are produced. The need to plant large areas quickly following a rain makes reduced or zero tillage techniques an attractive companion practice to opportunity cropping.

Conservation tillage is the strategy of reducing tillage and retaining stubble. It is an important means of increasing the efficiency of capture and retention of rainfall, as well as an effective measure for conserving soil, especially during fallow. The technology is well-developed and, while costs are somewhat higher than conventional tillage, yields are often higher in dry years. In good seasons, yields may be more N-limited than with conventional tillage unless additional N is supplied.

Nitrogen fertiliser use is gradually increasing, but there are still many farmers who have never used it. This is despite abundant evidence that grain protein and/or yield is depressed by N deficiency in many seasons on their farms. Its use is seen as expensive and risky.

Legumes in rotations are increasingly being viewed as an alternative source of N for cereals. Whereas grain legumes are well established cash crops, they do not leave much N behind. Except in the more favourable areas where lucerne is well adapted, there are major uncertainties about the technical and economic feasibility of pasture legume leys.

While these strategies are widely viewed by professional agriculturalists and some farmers as the most promising ingredients for good farming, only a few farmers appear to combine these imaginatively in the search for the 'ideal' system for managing soil water and nitrogen in this difficult environment. The situation is analogous to that in Africa. A major part of APSRU's research involves asking the 'why?' questions raised in our opening paragraph, and seeking answers in a number of ways.

APSRU's developing systems approach

APSRU's framework for R,D&E is shown in Figure 3. Although we have drawn heavily on Collinson's figure (Fig. 1), there are significant differences between APSRU's approach and Collinson's FSR processes. We see these as enhancements that both suit the needs of our farming and institutional environments, and utilise our particular research strengths.

We view farmers as our primary clients, but we are also concerned with the decision problems faced by a range of other decision-makers (Fig. 3 top) who have a stake in the performance of agricultural production systems and whose decisions influence, and are influenced by, farmers. These clients experience many of the same uncertainties as farmers, especially those concerning rainfall and prices.

Our aim is to contribute to better management and planning decisions (Fig. 3 right). In order to do this, we believe that professional agriculturalists must have sufficient understanding of the context and structure of decisions (Fig. 3 left). In general, farmers have evolved simpler rules for the management of key technological components that are as effective as the more complex rules generated by professional R,D&E (Cox et al. 1993a). In many cases, the farmers' rules are likely to be more effective because they recognise better the interdependence between the use of different components, and the open character of agricultural production systems. What we do needs to fit in with farmers' existing models or clearly demonstrate just how our way of doing things is better.

Simulation of agricultural production systems is an important ingredient of our approach (Fig. 3 bottom). Other papers in this workshop provide a comprehensive account of where we are in the development of this capability. We take a utilitarian approach to modelling: we use process models when and where this provides a research advantage. As was clear from the paper by Jones et al. (these Proceedings), we have been conducting experiments in farming systems research longer than we have been using models, but we found that experimentation has serious limitations in addressing many of the important issues.

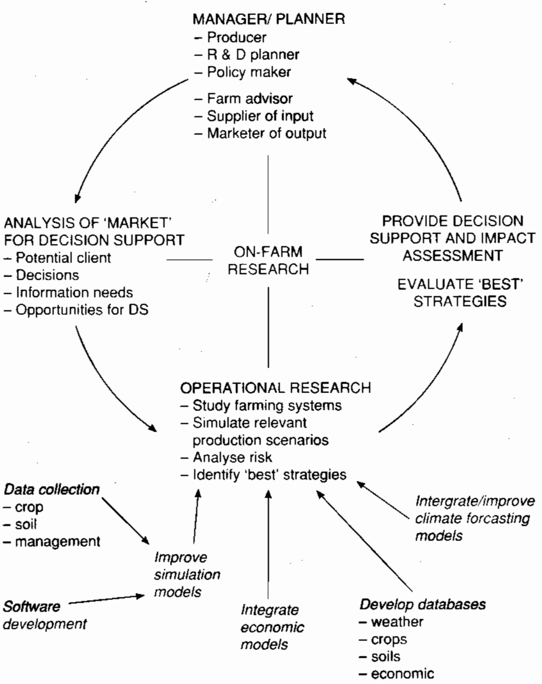

Figure 3. APSRU's framework for client-oriented R,D&E aimed at improving management of production and associated processes in an agricultural system.

An example is the difficulty of using experiments to assess the economics of N fertiliser where seasonal water supply is variable and unpredictable. Fertiliser response and net returns vary from strongly positive to strongly negative, and repetition for long sequences of years is needed to find an optimal strategy. Using historical weather records and models of maize and sorghum to predict grain yield under widely differing water and soil N conditions, Carberry et al. (1991) showed that the economic prospects for dryland cropping in a region of northern Australia are not sufficient to warrant further agricultural development. The provision of equivalent information experimentally would have required 400 000 plots (locations, times, years).

Recognition that simulation models can complement and add value to field experimentation in FSR has been recognised by others (Collinson, in Ruthenberg 1980; Anderson et al. 1985; Waddington 1992). But practitioners of FSR have judged, with rare exception, that the cost of getting models to a stage where they could do the job reliably was prohibitive (Collinson 1982). Like some before us (e.g. IBSNAT; Thornton 1991), we have decided to invest in the development of this capability. This has involved identifying the best biophysical models available with which to start and then testing and modifying these to improve prediction in the semi-arid tropics and subtropical regions in which we work. While adequate prediction of crop performance is critical to the utility of these models, we also have a strong focus on the simulation of soil processes (especially water balance, erosion and nitrogen balance) as they are influenced by management. We have built a novel software environment (APSIM) for developing, testing and using crop and other component models in systems research (McCown et al. 1993). This further reduces the overheads in using models in operational research within FSR (Fig. 1 centre).

We draw heavily from operational research in our systems approach (Fig. 3 bottom). This involves study of the performance of farming systems primarily in terms of production efficiencies, production and price risks, and cumulative effects on the soil resource. The emphasis is on the economic consequences of alternative actions over time. This is the starting point for addressing the question 'why don't more farmers invest more in soil fertility?'

Systems Research on Soil Fertility Management and Restoration

We are trying to find out, in the croplands of both Australia and Africa, whether farmers who appear to be underinvesting in soil enrichment understand their economics better than professional observers or whether they do not adequately appreciate the benefits of nutrient inputs and/or the penalties of continued exploitation of their soils. The answers have important implications for agricultural extension and for policy development. Achievement of this research aim is made difficult by spatial variation in circumstances between farms, and even between paddocks, which cause variation in benefits and opportunity costs. But an even greater obstacle to clarity is the variation in response to N inputs caused by unpredictable variation in seasonal rainfall.

Our approach in Australia to research on the management of soil fertility decline involves on-farm experimentation with farmers (Fig. 3 upper centre), especially on the costs and benefits of nitrogen inputs. Many farmers do experiments and even more have experiments in mind. We offer support for, and enhancements to, farmers' experiments, actual or latent. Both the content and the design of simple on-farm experiments are set by the farmers, subject to some revision after negotiation with researchers (Cox et al. 1993b). Treatments are negotiated with, and managed by, the farmers. Researchers help in planning, monitoring, interpretation of the results, and generalisation to other years and other sites. Experimental treatment areas are often simple splits of commercial paddocks. These usually involve N fertiliser rates in relation to paddock history, time of application, or crop species. Of particular interest are trends over time in responses to applied N following a legume crop or pasture, or a dry year when little or no N is used by the crop.

Although this is an attractive way of keeping research relevant to practice, there is no mystery as to why so little work of this kind has been done. First, no matter how obvious the treatment differences, variation in water supply among seasons and the interaction between N and water supply are so great that it is difficult to attach much strategic meaning to the outcomes during an inevitably short experimental period. Second, this approach violates the assumptions of classical statistical analysis required to isolate the yield variance attributable to treatments, i.e. replication and randomisation. The simulation model is used to compensate for theoretical deficiences in experimental designs. The model is configured for the soil properities and initial conditions, the crop cultivar, and for each management treatment successively run using weather data measured during the experiment. To the degree that the model successfully simulates the experimental results, both experimental and uncontrolled variation are also simulated by the model. If the experimental results are simulated satisfactorily, simulation of the experiment in all the years for which rainfall data are available provides a means of identifying superior management strategies.

A similar procedure provides a way to estimate the value for a decision about fertiliser use of the information in a seasonal weather forecast such as that based on the Southern Oscillation Index (SOI) (Hammer et al. 1991). This was demonstrated by McCown et al. (1991) for Response Farming in Kenya. The modelling approach provides a means of comparing management strategies in terms of long-term effects on productivity as influenced by erosion (Littleboy et al. 1992) or by changes in soil organic N (Probert et al. these Proceedings). While these last two effects are of interest to farmers with a long-term view of the productivity of their land, the broader community also has a stake in the way in which agricultural land is used, and is paying increased attention to these issues. In Australia, farmers are increasingly conscious of this pressure.

In Africa, several lines of research stand out as having high potential benefits for the amelioration of soil fertility decline.

1. Find cost-effective ways for more efficient capture, storage and use of manure on crops, taking into account the effects on the main source of manure, the pasturelands, which are also suffering nutrient depletion.
2. Use experiments to test various FASE (Fertiliser-Augmented Soil Enrichment) strategies (McCown et al. 1992) for combining applications of chemical fertiliser with manure, crop residues and composts; and use simulation to facilitate economic comparisons of these technologies over longer sequences of highly variable years.
3. Provide a modelling framework to extrapolate the results of research on biological strategies for soil enrichment. These include various legumes in rotations, legumes as intercrops, and trees in cropping systems.
4. Research the economics, including evaluation of the risks, of alternative soil enrichment strategies for different levels of inputs, and cost and price scenarios. Clients include farmers, R,D&E institutions and policy-makers.
5. Provide inputs to analyses that contribute to formulation of improved national policies on agricultural commodities, food security and fertilisers.
6. Communicate with policy-makers that no achievements in agricultural R,D&E can negate the need for some fertiliser inputs if farming is to be sustainable. And keep this on the policy agenda.

In APSRU, we are attempting to bring the complementary approaches of FSR and computer simulation together to address the deficiencies of both. Outstanding issues include: (1) the feasibility of constructing models of farming systems that are both sufficiently realistic for operations research and which reflect the way in which farmers see the problems of managing their systems; (2) the need to combine economic and ecological perspective; (3) the need to combine our new skills in crop modelling with more traditional economic models for operations research; (4) the need to develop and use these tools to improve communication between farmers and researchers rather than isolating them still further; and (5) to design and use tools that support intervention at different scales, ranging from individual farmers and farmer groups to local, regional and national policy.

Conclusion

It is clear that there is disappointment in both national and international R,D&E organisations that FSR has not resulted in greater change in the way farming is practiced in southern Africa. But it is most important that this be interpreted as limitations of an approach that has provided, and will continue to provide, a valuable framework for research. In Australia, we are using a version of the FSR framework to structure our research on the management of our agricultural production systems. We see the systems approach of Figure 3 as an adaptation which retains the strengths of both the anglophone and francophone FSR schools. It will become more effective as the operational research capabilities mature and as it becomes more firmly embedded in a participatory design process.

The success of Australia's APSRU approach requires models and thinking that are up to the task. Progress in development is evident from previous papers in this workshop. The main technical deficiencies of models for assisting FSR in southern Africa (Waddington 1992) are dealt with in APSIM (extreme N deficiency, rotations, intercropping, weed competition, and crop–livestock integration, as well as erosion). However, much work is needed to see how well these models predict over a wide range of circumstances. In Australia, networks of stakeholders in a better systems research approach are emerging to test and adapt these models and to develop innovative ways of using them to support both participatory on-farm experimentation with farmers and the management of experimental databases. Improved communication is an essential component of the approach.

Farming systems in northern Australia and much of Africa share important problems: declining soil fertility and productivity, and substantial risks associated with any private investment in soil fertility improvement. We believe that the eclectic approach we are developing is a reproducible and transferable research methodology that will be widely applicable both in Australia and Africa.

References

Anderson, J.R., Dillon, J.L. and Hardaker, J.B. 1985. Socioeconomic modelling of farming systems. In: Remenyi, J.V. ed., Agricultural Systems Research for Developing Countries. Proceedings of an international workshop held at Hawkesbury Agricultural College, Richmond, NSW., Australia, 12–15 May 1985. ACIAR Proceedings No. 11, 77–88.

Biggs, S.D. and Farrington, J. 1993. FSR and the rural poor. Journal for Farming Systems Research-Extension 3 (2), 59–82.

Broekhuyse, J. Th. and Allen, A.M. 1988. Farming Systems Research on the northern Mossi Plateau. Human Organization. 47 (4), 330–342.

Carberry, P.S., Cogle, A.L. and McCown, R.L. 1991. Future Prospects for Cropping in the Semi-arid Tropics of North Queensland. Final Report to the Australian Rural Industries Research and Development Corporation.

Checkland, P. 1981. Systems Thinking, Systems Practice. Chichester: Wiley.

Checkland, P.B. and Scholes, J. 1990. Soft Systems Methodology in Action. Chichester: Wiley.

Collinson, M.P. 1982. Farming systems research in Eastern Africa: The experience of CIMMYT and some national agricultural research services, 1976–81. MSU International Development Paper No. 3.

Cox, P.G., Garside, A.L. and McCown, R.L. 1993a. Market research for decision support for dryland crop production in Central Queensland: a preliminary report. Proceedings 7th Australian Agronomy Conference, Adelaide, September 1993, 332–335.

—1993b. Participatory design of an agronomic on-farm research program in Central Queensland. Proceedings 7th Australian Agronomy Conference, Adelaide, September 1993, 325–327.

Hammer, G.L., McKeon, G.M., Clewett, J.F. and Woodruff, D.R. 1991. Usefulness of Seasonal Climate Forecasts in Crop and Pasture Management. Proceedings of Conference on Agricultural Meteorology, University of Melbourne, Melbourne, 17–19 July 1991.

Littleboy, M., Silburn, D.M., Freebairn, D.M., Woodruff, D.R., Hammer, G.L. and Leslie, J.K. 1992. Impact of soil erosion on production in cropping systems. I. Development and validation of a simulation model. Australian Journal of Soil Research. 30, 757–774.

Lynam, J.K. 1978. An analysis of population growth, technical change, and risk in peasant, semi-arid farming systems: a case study of Machakos District, Kenya. PhD Thesis, Stanford University, California.

Matlon, P.J. 1987. The West African semiarid tropics. In: Mellor, J.W., Delgado, C.L. and Blackie, M.J. ed. Accelerating Food Production in Sub-Saharan Africa. Baltimore: Johns Hopkins University Press, 59–77.

McCown, R.L. 1991. Research in a farming systems framework. In: Squires, V. and Tow, P. Dryland Farming — a systems approach. An analysis of dryland agriculture in Australia. Sydney University Press. Ch. 18, 241–249.

McCown, R.L., Freebairn, D.M. and Hammer, G.L. 1992. A framework for research on improved management of agricultural production systems. Proceedings 6th Australian Agronomy Conference, Armidale, February 10–14, 1992, 214–221.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D. and Huth, N.I. 1993. APSIM: An agricultural production system simulation model for operational research. Proceedings International Congress on Modelling and Simulation, Modelling Change in Environmental and Socioeconomic Systems. University of Western Australia, Perth, 6–10 December 1993.

McCown, R.L., Keating, B.A., Probert, M.E. and Jones, R.K. 1992. Strategies for sustainable crop production in semi-arid Africa. Outlook on Agriculture 21, 21–31.

McCown, R.L., Wafula, B.M., Mohammed, L., Ryan, J.G. and Hargreaves, J.N.G. 1991. Assessing the value of a seasonal rainfall predictor to agronomic decisions: the case of response farming in Kenya. In: Muchow, R.C. and Bellamy, J.A. ed. Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics. CAB International,Wallingford. 383–409.

Norman, D. and Collinson, M. 1985. Farming Systems Research in theory and practice. In: Remenyi, J.V. ed., Agricultural Systems Research for Developing Countries: proceedings of an international workshop held at Hawkesbury Agricultural College, Richmond, NSW, Australia, 12–15 May 1985. ACIAR Proceedings No. 11, 16–30.

Remenyi, J.V. 1985. In: Remenyi, J.V. ed., Agricultural Systems Research for Developing Countries: proceedings of an international workshop held at Hawkesbury Agricultural College, Richmond, NSW, Australia, 12–15 May 1985. ACIAR Proceedings No. 11.

Remenyi, J.V. and Coxhead, I. 1985. Farming Systems Research in Australia: results of a survey. In: Remenyi, J.V. ed., Agricultural Systems Research for Developing Countries. proceedings of an international workshop held at Hawkesbury Agricultural College, Richmond, NSW, Australia, 12–15 May 1985. ACIAR Proceedings No. 11, 96–107.

Ruthenberg, H. 1980. Farming Systems in the Tropics. 3rd Ed.. Oxford: Clarendon Press.

Thornton, P.1991. Application of crop simulation models in agricultural research and development in the tropics and subtropics. International Fertilizer Development Center. Paper 15. 23 p.

Waddington, S.R. 1992. The future for on-farm crop experimentation in southern Africa. Paper presented at the CIMMYT FSR Networkshop on Impacts of On-farm Research, Harare, Zimbabwe, 23–26 June 1992.

ACIAR–SACCAR Workshop, Harare, 1993

Working Group Reports and Discussion

THREE working groups, each of 12-14 persons, were formed and chaired by Dr Nkwanyana (SACCAR), Dr Harmsen (ICRISAT) and Dr R. K. Jones (CSIRO). The groups concurrently discussed the following topics.

1. Defining aims and priorities for future research in dryland farming — after reviewing present activities.
2. How to develop research-extension-farmer linkages which could better utilise research output.
3. Needs for changes in OFR methods with a simulation modelling approach.
4. Training needs in the use of modelling techniques.
5. Opportunities for increased cooperation, both on a regional scale (east and southern Africa) and through broader international agencies.

Reports of each of the three groups were presented and discussed in plenary session. The following pages summarise the three reports and the discussion which was ably led by Drs McCown, Shumba and Waddington. The reports and discussions focused on smallholder farming systems in semi-arid areas of southern Africa.

1. Review of major problems of dryland farming in Southern Africa

Climatic problems

- — insufficient, variable total seasonal rainfall
- — unpredictable variations in rainfall patterns within seasons

Ecological problems (due to increasing human pressure on land)

- — deforestation
- — overgrazing
- — declining fallow periods
- — inappropriate farm decisions
- — unsustainable management of natural resources

Soil problems

- — erosion by wind and water
- — low inherent nutrient status (especially N and P), low fertiliser use, soil fertility decline
- — low organic matter and associated soil physical problems

Socioeconomic problems

- — limited cash resources
- — limited labour resources
- — limited draught power
- — poor education
- — insecurity of land tenure

Deficiencies in past research

- — lack of integration of climatic data in ongoing research
- — unexplained variations in results
- — lack of appropriate systems research on resource management

2. Current research directions

Crop improvement

Substantial progress has been made in producing improved hybrids and Open Pollinated Varieties (OPVs) of maize and of sorghum and millets. These have the potential for widespread impact on farm production, although production stability in the semi-arid regions is an elusive goal.

Agronomic practices

Varied results of experiments on fertiliser use, moisture conservation techniques, plant populations and intercropping all suggest a need for a more integrated, quantitative modelling approach. This would embrace the fluctuating levels of moisture-nutrients-plant populations and predict their interacting effects on crop growth and yield at widely different locations.

Improving research efficiency

Current assessments identified a general need to improve the impact of integrated research and its relevance to small-holder farmers. Also a need to reduce research costs and increase coverage of the problems of smallholder farmers was recognised. The introduction of a crop simulation modelling approach could have a useful place in upgrading the cost-effectiveness and overall impact of research in the drier agricultural areas of the region.

Sustainability

Future research will need to place greater emphasis on the design of sustainable farming systems, with a balanced approach to natural resources management.

SACCAR

SACCAR has been successful in coordinating commodity-based research e.g on crop improvement in sorghums and millets (SADC–ICRISAT), beans (SADC–CIAT) and cowpeas and groundnuts (SADC–IITA). The more holistic, farming systems adaptive-research approach that will be needed in the future may prove less amenable to regional coordination.

3. Aims and priorities for future research

Focus

Smallholder farming systems in seasonably dry (semi-arid) environments of southern Africa (SADC).

Goals

Improve overall natural resources management through an integrated approach:

- — improve soil fertility management and arrest its decline
- — reduce climatic and economic risks through better risk management
- — improve soil and water conservation, with greater emphasis on water-use efficiency.

Strategies

- Improve research coordination
  - — catalogue existing soil fertility projects and look for collaborative opportunities, e.g. through SPAAR, Rockefeller
  - — promote networking through the SADC region.
- Promote the use of modelling techniques that will concentrate attention on soil fertility in the context of climatic uncertainties and economic risks, and so add value to on-farm research.
- Assess possible agricultural interventions in the context of overall sustainability and management of natural resources.
- Work together with end-users (farmers, extension workers, politicians and policy makers) in developing tools for deciding strategies and implementing R&D.
- Educate donors, policy makers, and politicians on the need for long-term support for soil fertility research and natural resource management, highlighting successful examples where possible.

Objectives

- Quantify the extent of (and rates of) nutrient depletion, organic matter decline and physical/structural changes in the soils of dryland cropping systems (on-farm, not on-station).
- Employ climatic variability and economic risk analyses to assess the integrated outcomes of possible interventions to arrest soil fertility decline.
- Improve crop management, plant genotypes and the effectiveness of rainfall in cereal and legume cropping systems to increase productivity and improve fertiliser use efficiency.
- Broaden the scope of soil fertility research away from a commodity or cropping focus to a broader natural resources management approach, possibly involving agroforestry and/or animal production systems.
- Build and maintain relevant databases (crops, climate, soil characteristics, vegetation) and develop modelling techniques to assist in reaching the listed objectives.
- Use the databases and appropriate simulation models to create various scenarios and options for use as decision tools by policy makers, e.g. policy analysis on fertiliser costs and supplies and grain prices. Use the same tools to guide credit organisations, e.g. AFC in Zimbabwe, in managing schemes relating to soil fertility and climatic risks in different agroecological zones. Governments could use models preferentially to target subsidies to smallholders in areas where they could have the greatest economic impact.
- Educate communities of the region on the reality of soil fertility decline and the opportunities for limitations to technical solutions, and the implications of current farming practices. Special targets would be:

— policy makers and politicians
— extension workers and farmers
— school students and teachers (with practical demonstrations of improved technologies, including fertilisers, and tree planting programs)

4. Research, extension and farmer linkages

- The problem in Zimbabwe and Malawi is the linear model, i.e. researchers–extension–farmers. Adaptive research teams in Malawi provide a means of linking farmers to the researchers. The committee for on-farm research and extension (COFRE) exists in Zimbabwe. These initiatives can be built upon.
- The problem of research-extension being divided into commodity teams and disciplinary groups has to be replaced by a more integrated approach.
- Training and visit workers (T&V) could bring back current problems to researchers for analysis using models (for short-term response). It is important to develop this linkage.
- By incorporating computer simulation into T&V programs the time it takes to answer farmers' problems (short-term response) could be reduced. Eventually, information could be provided on tactical management (through a Decision Support System). Extension workers will not expect to use the models themselves but will work with researchers. There is thus a need to train extension officers and tertiary students in the possibilities of the models.
- Modelling efforts at universities should be promoted.
- Models could therefore be used at four levels:

  — to assist learning and interaction between researchers
  — to strengthen adaptive/applied research
  — to influence policy decisions
  — to support extension in managing recommendations

5. Changes in OFR methods needed with a modelling approach

Benefits of a modelling initiative

— overcoming the site-specificity of conventional experimental approaches
— a long-term climatic perspective is possible
— overall resource management can be improved
— a scenario analysis can reduce the need for, and extent of, field experimentation
— radical new options can be examined, e.g. new systems
— linkages with networks are facilitated.

Costs–changes needed

— a few, very detailed, research station experiments in the development phase
— many 'intermediate' detailed experiments (IBSNAT, MDS approach) in the application phase
— there is still a benefit-cost advantage because, with rigorous selection of sites to represent broad production systems and agroecological zones, fewer experiments are needed to extrapolate across zones
— guidelines are needed, e.g. for rigorous collection of MDS from on-farm experiments and selection of sites
— a periodic reassessment of models is needed.

6. Training needs for a modelling approach

This can be organised through SACCAR.

Ongoing and planned activities

— course on use of models in agronomy organised by SADC–LWMP (with ACIAR/CSIRO involvement) in November 1993
— COMMCION networking with emphasis on creating a climatic database
— IFDC training on the use of CERES-Maize in Malawi and Alabama

Further needs

— build a university capacity to teach modelling and develop models in collaboration with NARS
— use of soil fertility depletion studies as a vehicle for training nationally and
— training of trainers using hands-on collaborative research and/or secondments with a modelling group
— long-term training opportunities in collection of MDS (technical training), software use and database development.

7. Scope for cooperation

National and regional (direct SACCAR involvement)

— assess what is being done currently
— improve communication (across departments and ministries)

- encourage use of common methodology, and sharing experiences and resources
- promote a modelling emphasis within the existing networks.

International

- catalogue and analyse current and planned activities
- improve Africa–Asia linkages mediated through IARCs
- assist transfer of modelling technology and networking
- Australia (ACIAR–CSIRO) could contribute training and continuing model development, exploiting its comparative advantage in research on semi-arid mixed farming systems.

ACIAR Proceedings Series
Recent Titles

No. 31. Bacterial wilt of groundnut: proceedings of an ACIAR/ICRISAT collaborative planning meeting held at Genting Highlands, Malaysia, 18–19 March 1990. K.J. Middleton and A.C. Hayward (ed.) 58 p., 1990.

No. 32 Forages and plantation crops: proceedings of a workshop held at Sanur Beach, Bali, Indonesia, 27–29 June 1990. H.M. Shelton and W.W. St,r (ed.) 168 p., 1991.

No. 33 Technologies for sustainable agriculture on marginal uplands in Southeast Asia: proceedings of a seminar held at Ternate, Cavite, Philippines, 10–14 December 1990. Graeme Blair and Rod Lefroy (ed.) 128 p., 1991.

No. 34 Buffalo and goats in Asia: genetic diversity and its application. Proceedings of a workshop, Kuala Lumpur, Malaysia, 10–14 February 1991. N.M. Tulloh (ed.),144 p., 1991.

No. 35 Advances in tropical acacia research: proceedings of a workshop held in Bangkok, Thailand, 11–15 February 1991. J.W. Turnbull (ed.), 234 p., 1991.

No. 36 Fungi and mycotoxins in stored products: proceedings of an international conference held at Bangkok, Thailand, 23–26 April 1991. R.B. Champ, E. Highley, A.D. Hocking, and J.I. Pitt (ed.) 270 p., 1991.

No. 37 Breeding technologies for tropical acacias. Proceedings of a workshop held in Tawau, Sabah, Malaysia, 1–4 July 1991. L.T. Carron and K.M. Aken (ed.), 132 p., 1992.

No. 38 Forages on red soils in China: proceedings of a workshop, Lengshuitan, Hunan Province, People's Republic of China, 22–25 April 1991. P.M. Horne, D.A. McLeod and J.M. Scott (ed.), 141 p., 1992.

No. 39 Newcastle disease in village chickens: control with thermostable oral vaccines: proceedings of an international workshop held in Kuala Lumpur, Malaysia, 6–10 October 1991. P.D. Spradbrow (ed.), 181 p., 1992

No. 40 Peanut improvement: a case study in Indonesia. Proceedings of an ACIAR/AARD/QDPI collaborative review meeting held at Malang, East Java, Indonesia, 19–23 August 1991. G.C. Wright and K.C. Middleton (ed.), 108 p., 1992.

No. 41 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. M.E. Probert (ed.), 138 p., 1992.

No. 42 Productive use of saline land. Proceedings of a workshop, Perth, Western Australia, 10–14 May 1991. Neil Davidson and Richard Galloway (ed.), 123 p., 1993.

No. 43. Pasteurellosis in production animals. An international workshop at Bali, Indonesia, 10–13 August 1992. B.E. Spencer, R.B. Johnson, D. Hoffmann and L. Lehane (ed.), 256 p., 1993.

No. 44 Bovine ephemeral fever and related rhabdoviruses. Proceedings of the 1st international symposium, Beijing PRC, 25–27 August 1992. T.D. St. George, M.F Uren, P.L. Young and D. Hoffmann (ed.), 141 p., 1993.

No. 45 Bacterial wilt. Proceedings of an international conference held at Kaohsiung, Taiwan, 28–31 October 1992. G.L. Hartman and A.C. Hayward (ed.), 381 p., 1993.

No. 46 Draught animal power in the Asian-Australian region. Proceedings of a workshop held in conjunction with 6th Asian-Australian AAAP Societies, Bangkok, Thailand. W.J. Pryor (ed.), 135 p., 1993.

No. 47 Biology and mariculture of giant clams: proceedings form a workshop held in conjunction with the 7th International Coral Reef Symposium 21–26 June 1992 Guam, USA. William K. Fitt (ed.), 154 p., 1993.

No. 48 Australian tree species research in China: proceedings of an international workshop held at Zhangzhou, Fujian Province, PRC, 2–5 November 1992. A.G. Brown (ed.), 226 p., 1994

No. 49 Sandalwood in the Pacific region: proceedings of a symposium held on 2 June 1991 at the XVII Pacific Science Congress, Honolulu, Hawaii. F.H. McKinnell (ed.) 43 p., 1994

No. 50 Postharvest handling of tropical fruits: proceedings of an international conference held at Chiang Mai, Thailand 19–23 July 1993. B.R. Champ, E. Highley and G.I. Johnson (ed.), 500 p., 1994.

No. 51 Diagnosis and Epidemiology of Foot-and-Mouth Disease in Southeast Asia: proceedings of an international workshop, Lampang, Thailand, September 6–9, 1993. J.W. Copland, L.J. Gleeson and Chanpen Chamnanpood (ed.) 209 p., 1994.

No. 52 Tuna Baitfish in Fiji and Solomon Islands: proceedings of a workshop, Nadi, Fiji, 18 August 1993. S.J.M. Blaber, D.A. Milton and N.J.F. Rawlinson (ed.) 136p., 1994.

No. 53 Coconut improvement in the south Pacific: proceedings of a workshop held in Taveuni, Fiji Islands, 12 November 1993. M.A. Foale and P.W. Lynch (ed.) 82p., 1994.