R5163 SAPS

MAINTENANCE OF SOIL FERTILITY AND ORGANIC MATTER

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Project Final Report to DFID
Project Number R5163

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CONTENTS

1. Administrative information

1.1 DFID Reference-number: R5163.

1.2 Project Title: Maintenance of soil fertility and organic matter.

1.3 Organisation: The Department of Soil Science, The University of Reading, PO Box 233, READING, RG6 6DW.

1.4 Project Leader: Professor PJ Gregory

1.5 Full-time staff: GP Warren, SS Atwal.

1.6 Collaborating Institutions

(i) Kenya Agricultural Research Institute, Embu Regional Research Centre, PO Box 27, Embu, Kenya: SP Gachanja (Director); JW Irungu, J Muthamia, FM Kihanda (Research Scientists); AN Micheni, E Njiru (Technical Officers).

(ii) Kenya Agricultural Research Institute, National Agricultural Research Laboratory, PO Box 14733, Nairobi, Kenya: JN Qureshi (Director).

1.7. Project locations

Field work: Sites of the former Dryland Applied Research and Extension Project (DAREP) in Lower Embu and Tharaka-Nithi Districts, Kenya (operated by KARI Embu RRC and DFID).
Laboratory work: Department of Soil Science, University of Reading, UK, and KARI National Agricultural Research Laboratory, Nairobi.

2. Summary

Semi-arid sub-Saharan Africa needs cropping systems that can maintain productivity over many years to reduce the risk of crop failure. This project was done in the environment of resource-poor farmers in Eastern Kenya, in collaboration with an adaptive programme. Socio-economic data indicate that many farms here are below the size required to support a family with existing practices.

Soil organic matter (SOM) is the principal reservoir of N required by crops and it improves both the availability of other nutrients and soil physical conditions. Ideally, levels of SOM should be maintained. The project was strategic and aimed to quantify the dynamics of SOM and nutrients under arable cropping in semi-arid conditions and relate the changes to the use and management of manures, fertilizers and residues. In long-term experiments, cereal and cereal/legume cropping systems received different rates of manure, and the soils were analyzed to investigate changes in fertility.

The activities were as follows:

1. Collaboration was undertaken with the Kenya Agricultural Research Institute, involving the Embu Regional Research Centre running field experiments and the National Agricultural Research Laboratory doing crop and soil analysis.
2. Soil was extensively characterised at the research sites.
3. At the field level, we collaborated with DAREP, the ODA (DFID) adaptive programme. This included (i) diagnostic surveys to assess soil fertility as experienced in farmers' fields, and (ii) technical co-operation with the training of two scientists at the Centre (one PhD, one MSc).
4. Studies of soil N dynamics in the field were made, in relation to weather pattern and SOM.
5. Soil N availability and crop growth were measured and modelled with the PARCH model, in collaboration with Nottingham University.
6. Soil C, N and P were measured on samples taken annually at all sites, and crop N and P for nutrient balance studies.
7. SOM turnover was modelled in collaboration with Rothamsted Experimental Station (UK).
8. Agronomic results were reported in the DAREP Technical Reports and the Project Workshop.
9. A workshop was held in Embu for dissemination and criticism of the results by local, national and international participants.

Natural soil fertility was highly variable. Modest amounts of goat manure usually increased crop yields, and always increased soil fertility and the responses varied significantly between soils. The crop response was due to the manure-P at one site, and to manure-N at five sites. Major losses of N occurred at the start of the growing season, especially with over 5 t ha^{-1} manure. Mineral N was subject to large losses, and so the potential for the integration of mineral N fertilizer into the cropping system needs further research. Cropping systems are required which can capture some of the mineral N flush at the start of each season. Losses of P appeared small and supplementary use of fertilizer P can reduce N losses.

Modelling of SOM turnover and P trends indicated that without remedial activities, soil fertility drifted down slowly, but increased easily in response to modest amounts of manure. Residual effects of manure lasted three years (six cropping seasons) after application.

Manure rates over 5 t ha^{-1}, containing 100 kg N ha^{-1}, resulted in no benefit to soil fertility, with respect to SOM or N. Improvement of soil fertility is best based on manure rates of < 5 t ha^{-1}, applied at intervals of two or three years, supplemented by mineral P fertilizers.

3. Background information

3.1. Developmental problem of soil fertility in semi-arid sub-Saharan Africa.

Inadequate soil fertility is a developmental problem because it limits crop yields and hence food supplies and the ability of farmers to generate income. Shifting cultivation is the traditional soil fertility management practice of the project region, as in many other parts of sub-Saharan Africa. Food crops are not grown continuously in one place: yields decline until a better return for labour is obtained by clearing bush for new fields (for a specific example identified within the project area, see DAREP 1995b, p106). The project area is typical of areas of sub-saharan Africa in that population is growing but food supply is not. Recent evidence (D. Hunt, University of Sussex, personal communication) in comparison with a historic study (Hunt 1974) indicates that senior farmers with much land can still obtain adequate yields with traditional methods because they literally have room to move: for them soil fertility is not a constraint. The area of arable land required to feed one person under traditional cropping is 1.20 ha (Buringh, 1989). But the majority of extended family (multi-occupier) households in Mbeere now have <2.5 ha: Hunt, pers. comm). Soil fertility is thus an increasing constraint. Soil survey data are available for some of the project area (de Meeter & Legger 1988; van de Weg & Mbuvi 1975). These data indicate a range of soil types, but provide limited fertility information and no information for relating soil type to nutrient management for arable crops.

The wider goal of the work - improvement of the reliability of food production in the project area - is a multifactor problem. In the context of Indian semi-arid lands, Venkateswarlu (1986) observed that there is a large positive synergism between (i) proper management (sowing, weeding, water), (ii) improved seed varieties and (ii) fertility improvements. It is recognized in Kenya that in arid and semi-arid areas (some 80% of the total land area), crop yields are significantly depressed by inadequate nitrogen and phosphorus in the soils (Siderius and Muchena 1977). There is at present emphasis on reducing risk for semi-arid climates through better use of water. Under even dryer conditions of West Asia and North Africa, water use efficiency was increased by fertilizer (Cooper et al 1987, Shepherd et al. 1987). In mechanistic terms, improving soil fertility economises on finite water resources because a higher percentage of water is diverted to the vigorous plant stand, instead of being lost by evaporation (Gregory, 1989). It is recognised that for the time being, resource-poor farmers of the project area do not have enough cash to buy fertilizer. However, fertility maintenance is a part of the route to better use of resources.

Thus the goal for this project was to generate information on fertility improvements and nutrient dynamics with locally available materials. There is a need for improved cropping systems that give some increase in yields but, equally importantly, can maintain their productivity without large outside inputs, and are thus more sustainable.

3.2. Scientific background

Crop yields in African dryland subsistence agriculture are inadequate as a result of loss of soil fertility. The problem has been recognized for some time and the review of Nye and Greenland (1960) remains a definitive discussion. Productivity decline is brought about by the breakdown of the traditional cropping systems, which have long fallow (*ie* recovery) periods. Rapid population growth has put pressure on land and marginal lands are taken into cultivation without inputs being applied or appropriate soil management practices (Ofori, 1995). Simultaneously, the loss of crop productivity means that soil cover is reduced resulting in environmental degradation by soil erosion. In fact, most issues related to agricultural sustainability are related to soil quality, resilience and the ability of soils to respond to inputs and science-based management (Lal & Stewart, 1995). Thus, in reviewing the need for long-term soil management research in Africa, Ofori (1995) observed that agricultural development cannot be planned without medium to long term considerations and that this can hardly be achieved without identifying the potential and constraints of soils.

SOM is an important regulator of numerous environmental contraints to crop productivity (Woomer et al 1994). The functions include: nutrient (N, P and S) retention and storage, improved aggregation giving better stability and water holding characteristics, leading to lower erosion risk, retention of available nutrient cations and absorption and neutralisation of toxic components, such as aluminium and manganese.

Since 1960, substantial additions have been made to the body of technical data regarding SOM, and these were reviewed in the context of this project (Leech and Jenkinson 1993). From this, it was concluded that (i) rather little data exists in the form of long-term field work that can be used to assess the true rates of change of SOM, but (ii) the returns of organic matter to soil in unimproved arable agriculture are less than 50% of returns pre-cultivation, leading to soil degradation. However, application of animal manures and composts can slow down or reverse the decline, as can inorganic fertilizers (because crop residues are increased as well as grain yields).

The correct description of SOM turnover is of widespread interest because of the global environmental implications. There is an increasing base of scientific knowledge about it, although this is biased towards the temperate climates and environmental protection. The tropical subsistence farmer is directly dependent on SOM from the viewpoint of soil as a food production medium. In the absence of fertilizer inputs, soil organic matter is the principal reservoir of available N and P required by crops. This project is to link understanding of SOM turnover to the fertility consequences of SOM in tropical soils. In these systems it is desirable to maintain SOM at higher levels, to increase the amounts of nutrients cycling, and maximise their utilisation and minimise losses. It is desirable to (i) maintain

SOM at better level, (ii) obtain a more closed nutrient cycle, and (iii) synchronise nutrient supplies via SOM with crop uptake. In response to this need, the project aimed to develop a better understanding of nutrient dynamics in tropical soils by providing new data focused on SOM.

The observed changes in SOM are the net effect of complex interactions of many environmental factors. In this situation, computer modelling of the systems is a valuable tool. The Rothamsted model (Jenkinson 1990) concentrates on soil based processes and although based on temperate conditions has proved to represent tropical soil changes satisfactorially. The CENTURY model is based on North American data, but it too has been used for tropical conditions (Parton et al. 1994) with some success. Nevertheless, there is a clear need for appropriate data to fully test and extend these models to the particular complexities of tropical subsistence farming, something which this project has addressed. The organic constituents of tropical soils do not possess any special qualities that set them apart from temperate soils (Theng et al 1989), rather, the relative pool sizes of the components differ in response to climatic factors. Therefore, methods of SOM investigation for temperate soils were applied in the present project.

4. Project Purpose

The formal purpose (DFID) was:

Semi-arid Purpose 2. Developing strategies to reduce risks through optimisation of land use and cropping patterns.

- Technologies to maintain or enhance soil fertility.

The project aimed:

- To predict better the amounts of organic inputs required to maintain soil organic matter and fertility in semi-arid soils. Maintenance of soil organic matter levels will increase efficiency and reduce risk in food crop production.
- To generate information on the management of plant nutrients in appropriate and sustainable cropping systems.

5. Research activities

5.1 Detailed descriptions

Full descriptions of the experiments and activities are given in Appendix 1, with analytical methods covered in the appendices relevant to the results. A concise overview is provided here.

5.2 Resources and expertise: allocation of work and responsibilities

KARI provided scientific and technical expertise in agonomy, field sites, local labour, laboratory and storage space and plant analyses. The work was performed in association with an existing ODA/KARI project, Dryland Applied Research and Extension Project (DAREP) so as to be more integrated with local agronomy and adaptive work. Reading University provided a Research Fellow, visiting Embu for intensive soil monitoring, data analysis and project management. Soil samples for long-term trend analysis were taken to Reading for maximum quality control (Appendix 13).

Supplementary work and collaboration with DAREP and NARP2 was achieved in the form of technical assistance provided to:

- A KARI PhD student at Embu (JW Irungu: Thesis completed in 1998, also Appendix 11).
- Short training in soil analysis methods to a KARI Technical officer (AN Micheni: see Appendix 9 for some results).

5.3 Field experiments

The field experiments are described in detail at Appendix 1. An outline of the activities follows:

5.3.1 Contrasting field treatments were maintained for several years to monitor changes in soil organic matter (SOM). The essential features of the field work are:

(i) An appropriate cropping system: a rotation of sorghum/cowpea followed by millet/green gram, which provides the main food crops of the region.

(ii) A treatment that builds up SOM (manure).

(iii) A treatment that brings about a decline in SOM (no manure).

This experiment originated in 1988 under EMI the Dryland Farming Project: we took advantage of the preceeding work to gain a perspective longer than the lifetime of this project.

5.3.2 Soils were sampled and analysed at intervals (usually annual) to follow changes in nutrient supply and SOM.

5.3.3 The data were fitted to the models (i) Rothamsted model of SOM turnover, over the full lifetime of the project and (ii) the PARCH model for a within-season study.

5.3.4 Long term sustainability was assessed from the stability of SOM and nutrient supplies, as described by the Rothamsted model in conjunction with trends in soil nutrients.

5.3.5 The manure experiment was replicated in 7 locations (originally 9) to test and model the effects of differences in soil. It may be noted that in the original concept notes it was only envisged that one site would be used, plus limited supplementary data.

5.3.6 A second field experiment was started at 2 sites, to provide data on the effects of crop residues alone and the rapid decline of SOM soon after clearing. The experiment formed a testing ground for work with the PARCH model (see below).

5.4 Model development

Instead of developing new models, we collaborated with the authors of existing, appropriate models. This gives better dissemination and acceptance. In particular we collaborated with Rothamsted, using their internationally renowned long-term SOM model. We collaborated with Nottingham University in development of the PARCH model to take account of within-season response to soil fertility, contributing to the soil N turnover submodel, developed with approriate datasets collected from the field experiments. Crop yields depend on water, fertility and other constraints in an integrated way, so the effects of soil fertility maintenance should be best represented by modelling in combination with the other constraints.

5.5 On-farm soil assessment

An outcome of the association with DAREP was the comparison of laboratory and farmers' assessment of soil fertility, reported below (Section 6.11 and Appendix 11).

6. Outputs

The key findings and conclusions are summarised here, with conclusions arising from the results. The research results are discussed in detail in Appendices 2 to 11.

6.1 Continuous manure application increased crop yields and soil fertility (N, P, K and organic matter: Appendices 2 and 4). However, soil fertility was still changing in the period four to seven years after manuring started, as indicated by results for organic C and extractable P (Appendices 5 and 7), so a new dynamic equilibrium had not yet been reached.

> *Investigations of sustainability as affected by the farmers' principal fixed natural resource, soil, must have a long term dimension. Special care must be taken with quality control in the soil analyses, to avoid bias between sampling years (see Appendix 13).*

6.2 Manure applied for four years had residual effects for at least three years (six cropping seasons) after the final application (Appendix 3).

> *Investigations of sustainability as affected by soil, must have a long term dimension. Manuring need not be carried out every season. At low application rates, nutrients surplus in the season of application are stored and not wasted.*

6.3 The high manure rate (10 t ha^{-1}) did not increase soil organic C and total N more than the low rate (5 t ha^{-1}) (Appendices 4 and 5). The N in the extra manure was therefore lost, as confirmed by surplus soil nitrate-N at the end of the growing season under the high manure rate (Appendix 6).

A low manure rate distributed thinly will conserve the nutrient value of the manure better than a high rate applied occasionally or to a small area.

6.4 The Rothamsted model for C turnover worked well in these soils at moderate manure rates (up to 5 t ha^{-1}), but was not satisfactory at continuous high manure rates (10 t ha^{-1}) (Appendix 5).

Some amendment to the model may be needed to account for the low stabilisation of C at high rates, and checked against a longer dataset.

6.5 The beneficial effects of manure were due to different mechanisms in different places: where soil P was low, the yield benefits were due to the P supplied; at other sites, the response to manure was inversely related to native soil N (Appendices 3 and 8). It is highly likely that such differences exist within farms as well.

Because fields differ in fertility, an adaptive, but scientific, approach is required to getting the best from inputs (manure or mineral fertilizer), rather than blanket recommendations.

6.6 Efficiency of N uptake was increased by improved soil P status. Native soil P, manure P and mineral fertilizer P all had this effect (Appendices 6 and 8).

The use of mineral P fertilizer (SSP, TSP, DAP) is justified in the region. Its introduction should be on a small, careful and site-specific basis because some fields will give no yield response. Consideration should be given to calibration of soil extractable P in relation to crop yields, as a guide for fertility improvement.

6.7 Mineral N supply in the soil is high at the start and finish of the seasons but low in the middle, ie. it is poorly matched to crop demand (Appendix 6). Losses of mineral N are high and thus mineral N fertilizers have a low chance of efficiency.

The use of mineral fertilizers based on N (CAN, urea) is not recommended at present since losses will be high. Extra research is necessary to find out how N inputs to the farming system can be incorporated out relatively efficiently. Methods to improve synchrony of nutrient supply are highly relevant.

6.8 Under intercropping (sorghum/cowpea and millet/green gram), the performance of the legumes (as a proportion of grain yields) varied between sites. Improvement of soil fertility by addition of manure had little effect on the legume proportion (Appendices 2 and 8). It could be beneficial to farmers if they could control the legume/cereal ratio for a better quality of food or economic return.

The influence of soil properties on the relative productivity of cereals and legumes requires additional investigation.

6.9 For P, nutrient balances were related to the trends in soil P. It was apparant that when manure was added, there was much unused P going to soil organic P fractions (Appendix 7). These become a major reserve of P that is partly available to crops. Little is known about these fractions of soil P and their potential mineralization rates. In turn, the availability of this combined P may influence plant growth and the efficiency of N uptake.

Further investigations of the organic P components and their dynamics are called for if there is to be better management of available P.

6.10 The "optimum" rates of manure application might vary greatly according to the costs and availability of manure as well as soil type (Appendix 2). Some mathematical relationships between manure rate and crop yield were outlined (Appendix 10), and in conjunction with economic and farming system data can be used to generate immediate choices and guidelines regarding manure rates, that can be selected appropriately to particular farms.

These aspects require investigation in an adaptive project utilising manure-response relationships (see Appendix 10) with major input from agricultural economics and farming systems approaches.

6.11 Interaction with DAREP and DFID/NARP2 activities enabled on-farm characterization of soil (DAREP 1995a, 1995b). Farmers identified fertile and infertile soil on their land and the most important difference between these categories was found to be soil organic matter (SOM) content (Appendix 11).

Participating farmers perceive soil fertility to be a limitation and their assessments correlate with certain chemical asssessments of soil fertility. Thus the aims of this project were shown to identify with farmers' interests.

6.12 Written Outputs. A list of publications and written outputs is given at Appendix 12.

6.13 Established field plots. The field demonstration of the effects of changes in SOM on crops is a unique resource, since soil fertility has been characterised and monitored for several years. This resource would take much time (10 years) and money to repeat. It is hoped that the plots can be used in a different way to contribute extra information on sustainability as determined by natural resource constraints (see sections 7.2 and 7.4.11).

6.14 Data storage. Crop and soil data covering the complete lifetime of Trial 1 (1988*ff*) are kept by KARI Embu RRC and The University of Reading, Department of Soil Science in paper form, and mostly also as Excel spreadsheet files. These data can be made available to interested researchers.

6.15 General conclusions regarding the sustainability of cropping.
Modelling of SOM turnover (Appendix 5, Figure 2) and P trends (Appendix 7, Figure 2) suggested that without remedial activities, soil fertility drifted down slowly, but it increased easily in response to modest amounts of manure. The residual effects of manure lasted at least three years and six seasons after application (Appendix 3). Manure seemed more effective than crop residues for increasing SOM (Appendix 4). Manure at rates over 5 t ha^{-1}, containing 100 kg N ha^{-1} resulted in no benefit to soil fertility, as regards C or N, whereas P and K always accumulated in the soils. Improvement of soil fertility is best based on manure rates of < 5 t ha^{-1}, applied at intervals of two or three years, supplemented by mineral P fertilizers where soil P is deficient.

7. Contribution of outputs to DFID goals

7.1 Developmental goals

The project was strategic, acquiring relevant natural resource information, rather than directly improving the situation of a particular group of people. It was targetted on a typical region of sub-Saharan Africa, in a semi-arid climate away from the centres of mainstream private-sector commercial activity and in locations where there are limited opportunities to participate in the cash economy. The ultimate beneficiaries are thus resource-poor rural communities who depend on subsistence farming. Soil is one of the most important natural resources for these people, since the agricultural potential of a farm is strongly determined by its soil fertility, which was found to vary very greatly. The project acquired essential information relevant to soil fertility changes on a short term (within-season) and longer-term (year-to-year) basis.

Furthermore, the comparison of farmers' and laboratory assessment of soil fertility (Section 6.11; Appendix 11) showed that farmers are well aware of soil fertility variations and changes, and their perception generally accords with objective analysis. Investigation of the dynamics of SOM to maintain or increase fertility is an objective that fits well with farmers' perception of the problem.

Additional adaptive stages are required and can be planned in the light of: (i) results; (ii) identified regional/national priorities, in the particular case by KARI and the NARP2 adaptive programme; and (iii) information from other projects in the target zone. Approriate farm-level advice (Section 7.3) and adaptive activities (Section 7.4) were developed at the Project Workshop.

7.2 Uptake pathways

(i) KARI Regional Research Centres.

The KARI centres concerned with dryland agriculture and soil fertility investigation are principal intermediate users. The results establish the natural fertility of these soils and the potential of manures to improve yield and reduce risk. KARI Embu RRC in particular will utilise the outputs for adaptive projects in its mandate area.

(ii) Local NGO's. Full results are being communicated with two NGO's which are active in the project area and have an interest in soil fertility: Intermediate Technology, Kenya (Nairobi based branch of the UK Charity) and Kamurugu Project, Iriamurai (an Italian mission funded development project in Mbeere District).

(iii) KARI National Dryland Farming Research Centre, Katumani.

It is intended that the two remaining project sites will be integrated with a major strategic + adaptive research project - CARMASAK (see 7.4.11) - funded by the Rockefeller foundation in colloration with Katumani and ICRISAT. Data supplied by this project, further measurents at the field sites and modelling by ICRSAT will add to wider understanding of dryland soil fertility dynamics, within the current KARI and CGIAR activities

7.3 Results of immediate use to extension and farming in the project area

This was intended as a strategic project, not an adaptive one, so a large output of practical farming techniques was not to be expected. However, based on the results, the following guidelines were developed at the Project Workshop and can be brought to farmers now, in the course of extension and adaptive work:

7.3.1 In the long term, it is better to spread manure thinly, rather than use very high rates, because N will be lost. However, rates up to 5 t ha^{-1} appear acceptable from this viewpoint (Finding 3).

7.3.2 Mineral fertilizers based on N are not at present recommended for use in the area because of high losses.

7.3.3 Modest amounts of P fertilizer can be useful. There are some soils that are very deficient, but many other soils are supplied adequately with P. On-farm, site-specific adaptive experiments with small areas and trial amounts of fertilizer are needed to find the places where P is required.

7.4 Suggested follow-up work

First priority activities: mostly suitable for adaptive projects

7.4.1 Monitoring long-term fertility dynamics (see output 6.2)

Annual soil sampling continued; it is highly preferable that existing management and analysis arrangements (KARI Embu RRC/Reading University) are maintained for continuity. Improve link with TSBF. Core funding for the sites is required, plus costs of annual soil analysis.

7.4.2 Relating nutrient balances to soil characteristics (see output 6.9).

The manure plots are a well-characterised test-bed for relating nutrient balances over the longer term to soil properties. This has shown a way forward and relevance for the NUTMON (KARI/Netherlands project) activities, which so far only deals with 1-year periods.

7.4.3 "Optimum" rates of manure application.

An adaptive project utilising manure-response relationships (Appendix 10) with an economic and farming systems approach is needed, to analyse the costs and benefits of different manure and crop sequences. This should establish a set of different, but all sustainable options that farmers can select and adapt to their own fields.

7.4.4 Changes in soil physical properties.

No work was done on detailed physical measurements of the soils such as infiltration rates and aggregation, because this project was oriented to aspects of soil chemical fertility aspects and there was no qualified and interested scientist to hand to take an interest. Some activity can now be developed through KARI NDFRC Katumani, with Dr G Okwach (see 7.4.11).

7.4.5 Manure-pest/disease interactions.

No work has been done on interactions with other limitations on yield and soil fertility. Other limitations such as pests, diseases and physical conditions combine to limit yields in the long term. Fertility changes slowly (see outputs 6.1 and 6.2) and secondary problems and interactions may develop, as already identified by farmers on visits to the sites. These experiments form an ideal opportunity to investigate long-term secondary effects. This is a subject area where adaptive approaches are particularly suitable.

Long-term plots and farmers' fields would be thoroughly assessed by farmers and crop protection experts. On-farm experimentation and monitoring by joint expert/farmer groups could be carried out. KARI Embu RRC, with Kamurugu Project and Intermediate Technology

(NGO's) to be the lead organisations. The latter two NGO's are increasing their activities related to soil fertility in Mbeere and Tharaka respectively.

7.4.6 Integration of mineral N and manure N fertilization (see outputs 6.6 and 6.7).

Testing of manure plus top-dressing, probably best as an adaptive project. Must be co-ordinated with NARL NUTMON activities: NUTSAL is in the immediately adjacent region. Mineral N in selected long-term plots of different fertility could be monitored for one or two seasons with top-dressed N.

7.4.7 Moisture/nutrient interactions.

Interaction of soil moisture content and N mineralization was clearly observed, in these areas of very variable rainfall. Studies of the interaction of water harvesting and nutrient supply are called for.

Research projects of a strategic and/or basic nature, where project data gives a strong justification

7.4.8 SOM change/decomposition in relation to climate and soil type (see outputs 6.3 and 6.4).

Measure SOM-C fractions (POM/Ludox?) and decomposition under incubation. Use also soil from other dryland sites. Suitable as a student project, TSBF and University of Nairobi to be involved.

7.4.9 Destination of immobilized/fixed P (see output 6.9).

Plot-level nutrient balances show that much of the P added in manure has remained in the soil but in non-extractable form. Its exact forms and their (re-)mineralization potential are unknown, and should be investigated by analysis of organic P. Basic/strategic research is needed, with co-operation of "Advanced" research centres (international level for specialist methods) and regional level (for broad comparisons and principles). Co-ordination through KARI NARC Muguga is suggested.

7.4.10 Legume/cereal performance (see output 6.8 above).

Investigation of soil factors that influence legume/cereal ratio; Glasshouse experiments to isolate climate factors; on-farm experiments to test management factors; cropping of long-term plots adjusted to complement on-farm work. Appropriate for a student or researcher project based at NARL. A relevant project proposal has been drafted.

7.4.11 Crop modelling and integration with KARI activities.

The project has run from 1993 to 1997 in association with the DAREP activities at KARI Embu RRC. The nature of the soils is now quite well known. The time is appropriate to integrate the remaining field sites with other KARI soil research activities. In this way, the experience can contribute to wider soil fertility issues. It is suggested that the field site activities be linked to the Katumani project CARMASAK (Collaboration on Agricultural Resouce Modelling and Applications in Semi-Arid Kenya; KARI/ICRISAT/APSRU (Australia)). CARMASAK deals with sustainability of dryland cropping, and discussions with that project show that several of the findings above are to be researched by CARMASAK.

7.4.12 Organic residues studies

The organic residues used were materials in the project area ie. goat manure and residues of the crops grown, but data on the actual amounts, composition and potential for nutrient release are limited. Some detailed surveys of certain of these properties are currently under investigation elsewhere in Kenya, particularly by the University of Nairobi and TSBF (Tropical Soil Biology and Fertility Programme). Contact is maintained with these investigators, with a view to identifying the best way to integrate SOM turnover results, residues data and methods of resource capture by food crops.

If, as mentioned above, the animal component seems important, there would be a need for expertise in animal nutrition in conjunction with agricultural system nutrient balance work. This would be readily possible through KARI Embu RRC because of (i) the relative integration of scientific disciplines at a small Centre and (ii) now-established networks of collaborating farmers provide a good human resource structure for this purpose in an adaptive context. It is hoped that application will be made for further funding, in collaboration with the KARI Embu Centre and other centres of local expertise, such as ILRI, TSBF and the University of Nairobi.

7.5 Wider dissemination

Results are being disseminated to the wider scientific and development community via these pathways:

(i) Journal publications.

(ii) Data input to network projects such as those of ICRAF and TSBF.

(iii) Description and announcement at appropriate meetings.

(iv) Personal discussion and demonstration on site with visits by National and Development agency representatives and scientists.

(v) The participatory farming systems methodologies, events and publications devised by

DAREP continue to create interest.

(vi) The Project Workshop, held in Embu in November 1997. The main project results were presented and then discussed by peer groups. The participants were drawn from KARI (several Centres and at all staff levels), Universities and International organisations. Ideas and recommendations that arose in the Workshop have been described above. The Workshop Proceedings will be issued during the first half of 1998.

8. Special acknowledgements

The project would have been quite impossible without the system of field stations run by local managers ("Field Assistants") that was set up by Vernon Gibberd (NRI) under the EMI (Embu Meru Isiolo) Project. The Field Assistants made possible the collection of such an extensive data set. Particular thanks are therefore due to S. Kimanthi, S. Kiraga, J. Mutisya, P. Mutwiri, S. Mwiti, P. Njoroge, J. Odhiambo and J. Ringera. Thanks are also due to V Gibberd and P Mutwiri who designed and set up the original Trial 1, which has proved to be the basis of this project and much more valuable than they had originally envisaged.

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INTRODUCTION TO THE PROJECT: "MAINTENANCE OF SOIL FERTILITY AND ORGANIC MATTER IN DRYLAND AREAS" AND ITS FIELD EXPERIMENTS.

1. Objectives and activities

The essential objective was to understand better the dynamics of soil organic matter (SOM) in semi-arid climates, with a view to improving the management of manures and crop residues. These organic inputs to soil are responsible for maintenence of the SOM as it is formed and decomposed by natural turnover. SOM is a vital component of soil and plays in important role in several aspects of soil, such as acting as a reservoir of nutrients (N especially), and assists in maintaining satisfactory soil conditions for plant growth, such as structure and pH. A number of objectives were described in the project proposals. The main ones, and the activities which were undertaken to provide relevant information and outputs are listed here.

1.1 Measurement of changes in SOM, nutrients, and rates of nutrient release.

- Soil characterisation for the initial 9 sites, to assess the effects of the preceeding 4 or 5 years of manure treatment.
- Annual soil analysis in 7 sites, looking for trends.
- Intensive study of nitrate dynamics in one season.

1.2 Correlation of the changes with crop yields.

- Yields and residues measured.
- Nutrient balances for crops measured.

1.3 Manipulation of SOM turnover to improve supplies of plant nutrients.

- SOM turnover modelled
- Issues discussed at this workshop.

1.4 Development of models for nutrient mineralization rates in relation to the cropping system.

- Work with Nottingham University on the PARCH model.

1.5 Demonstration of long term cropping with improved cropping systems and recommendations on the amounts of organic matter required to sustain them.

- Field experiments over an extended period.
- Crop response data.
- Interpretation of soil analysis and agronomy data.

2. Field work

The work was based around a pre-existing multi-centre field experiment located in semi-arid Mbeere and Tharaka-Nithi Districts of Eastern Province, Kenya. An additional field experiment was set up at the two sites with the lowest and highest natural fertility. The main features of the two experiments are summarised below (Sections 3 and 4).

The project location was chosen by NRI because it was desired to associate the research work with the participatory and adaptive project DAREP (Dryland Applied Research and Extension Project) at KARI Embu RRC from 1993 to 1996. The field sites were shared with DAREP. Advantage was taken of this link to add some on-farm measurements work, described in Section 5: (i) analysis of soil from farmers' fields, for two diagnostic surveys and (ii) soil analysis and scientific assistance in field experiments to assess N fixation by cowpeas.

3. Experiment 1: "Trial 1"

3.1 Introduction

The experiment was started in 1988/9 and is commonly called "Trial 1" since that was the name given in EMI (Embu-Meru-Isiolo Project) days. We have maintained the name and also most of the original treatment codes on the plots. This can be confusing to the outsider (M1 receives more manure than M2), but has reduced the chance of mistakes in management at the local level. An alternative coding will be introduced for journal publications.

There are two rainy seasons, which we have identified by the month of peak rainfall. They are (i) the "April season" from March to June and (ii) the "November season" from October to January. It is normally found that in the November season, the amount of rainfall is more and its distribution is better. The terms "Short" and "Long" rains are commonly used in Kenya, but have been avoided here, because in these areas the traditional "Long" season from March is the less favourable one for arable crops, and "Long" normally implies "better" in semi-arid climates.

3.2 Sites

Nine sites were selected by EMI as described by Gibberd (1995a) and in Ministry of Agriculture/ODA reports. They were as follows, with the starting season:

Gategi	11/88
Machanga	4/89
Mutuobare	11/89
Kamwaa	4/89
Kajiampau	11/88
Gacheraka	11/88
Kaanyaga	4/89
Kaaragankuru	11/88
Kirimbu	11/90

3.3 Design, 1988 - 1993

For full details see Gibberd (1995b). There were three manure treatments and three cropping systems, in a complete factorial design with three replicates. The manure treatments were:

M0 Control (no manure).
M2 Low manure rate: 5 t ha^{-1} applied annually every October.
M1 High manure rate: 10 t ha^{-1} applied annually every October.

Due to a change in plans while setting up the experiment, at sites which started before September 1989 (all except Mutuobare and Kirimbu) the 5 t ha^{-1} plots received an extra 10 t ha^{-1} manure in March 1989. This is because M2 was originally intended to be manure applied in March each year. Manure applied in October 1988 and March 1989 was acquired locally to each site. From October 1989, all manure came from goats housed in sheltered animal houses at the Ministry of Agriculture station at Marimanti, Tharaka. The total amounts of Marimanti manure used over four years (1989 to 1992) were 40 t ha^{-1} (high rate) and 20 t ha^{-1} (low rate), except at Kirimbu, where 30 t ha^{-1} (high rate) and 15 t ha^{-1} (low rate) were applied over three years.

Locally acquired manure is always highly variable, and if used (as in most agronomy work), differences between sites in the effects of manure are more likely to be the result of variations in the composition of the manure. In Trial 1, the same manure was used at all sites and all seasons from October 1989. This is an important feature of the experiment: *It is therefore possible to say that differences in results between the sites are largely due to the soil.*

The cropping systems were:

C1 Rotation with a legume planted in October and a cereal in March.
C2 Rotation with a cereal planted in October and a legume in March.
C3 Cereal/legume intercrop sown in both seasons.

The crop combinations alternated between sorghum (*Sorghum bicolor*, var. 954066) and cowpea (*Vigna unguiculata*, var. M66) for two consecutive seasons, followed by pearl millet (*Pennisetum typhoides*, var. KPM1) and green gram (*Vigna aureus*, var. N26) for two consecutive seasons. This cycle commenced with sorghum/cowpea in October 1988.

3.4 Main results from 1988-93

Crop yields were significantly increased by manure at most sites (Gibberd, 1995b). Intercropping yielded more grains than either sole-crop rotation and an economic analysis indicated that sorghum/cowpea with 5 t ha^{-1} manure gave the best return for the labour of manure application. The C1 rotation was the least productive, and therefore it was the one that was terminated after the April 1993 season. Differences between sites in the response to manure were tentatively ascribed to differences between soils in available P, based on preliminary soil samples taken in July 1992 to assess the suitability of the sites for the subsequent work.

Soil was sampled in all plots at the start of 1993 as part of the Maintenance of Soil Fertility Project (Appendix 2). Manure at 5 t ha^{-1} increased soil P and K almost everywhere, but C and N at some sites only. Extra manure (treatment difference M1-M2) increased P and K, but not C and N.

3.5 Design, 1993 - 1997

In 1993, Kaaragankuru and Kirimbu sites were closed by DAREP. The crop rotations C1 and C3 were changed to an annual cycle with intercropped sorghum/cowpea every November season and millet/green gram every April season.

In C3, the manure rates were unchanged, so the treatments designated C3Mx have a continuous run of intercropping with the same four crops from 1988/9 to 1997. In the former C1M1 and C1M2, manure application was stopped to examine the rate of run-down of soil fertility after manuring. NPK fertilizers were added in the former C1M0 at the same rate of N and P as in C3M2, to test the possible benefits of organic over inorganic fertilizers. The new treatments were:

C3M0	Control
C3M2	Continuous manure (5 t ha^{-1})
C3M1	Continuous manure (10 t ha^{-1})
C3F (ex-C1M0)	Fertilizer from 1993 (N & P at the same rate as in C3M2)
C3R2 (ex-C1M2)	Residual manure: 1989-1993 only (5 t ha^{-1})
C3R1 (ex-C1M1)	Residual manure: 1989-1993 only (10 t ha^{-1})

The C2 treatments remained unchanged, rotating between the four crops as before, but the plots were not used for soil studies. They had to be maintained since they were randomised with the other experimental plots, and they are available as a soil resource for future experiments.

C2M0 Control
C2M2 Continuous manure (5 t ha^{-1})
C2M1 Continuous manure (10 t ha^{-1})

3.6 Major findings, 1993-7

Fuller details are reported in Appendices 2 to 10. Regarding the agronomy, it may be noted here that:
(i) Crop yields continued to be significantly increased by manure (Project Summary Paper 1).
(ii) There were differences between soils in the effect of manure, and the differences could be related to soil properties (Appendix 2).
(iii) The composition of the crops (N, P, K; grains and residues) was not significantly affected by manure use, so there was little "luxury uptake" of nutrients added in manure at the rates used (Report: Warren and Qureshi, 1995).

3.7 Conclusion

Trial 1 has been at the core of the project work, and the data accummulated in 1993-7 benefit from the continuous run since 1988/9. These data are a unique resource, since no other manure experiment has been carried out for such a long time in semi-arid East Africa.

3.8 References and reports: Trial 1.

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4. Experiment 2: "SOM Experiment"

4.1 Introduction

This experiment was started in February 1994. It was planned in order to supplement Trial 1 by giving information on the effects of crop residues alone, and to incorporate elements of the TSBF (Tropical Soil Biology and Fertility Programme) "Setsom" design, for long-term assessment of SOM dynamics. Two sites are used, Machanga and Mutuobare, the ones with the lowest and highest soil P, respectively. That contrast is examined in Appendix 8.

4.2 Treatments.

The treatments are as follows, aranged with three replicate blocks:

B: Bush - Natural vegetation.

This area is fenced off and left as a wilderness. It will be useful in the future, to represent the soil at the start of the experiment.

F1: Grass Fallow - Vegetation cut, soil undisturbed.

At the start (March 1994), all vegetation was cut to ground level and the cut material removed. Subsequently, fresh plant growth is cut to the ground once or twice per rainy season, without disturbing the soil. Plant material which grows on the plot is left on the plot. Organic debris which falls on the plot naturally (twigs and leaves from nearby trees) is also left on the plot.

F2: Bare Fallow - Tilled regularly.

All vegetation was removed from the plots and the soil cultivated with a forked jembe. Fresh plant growth and any other organic material which falls these plot is removed. Once per month, the soil is cultivated again with a jembe, as if a seed bed is being prepared. This treatment corresponds to the TSBF "Killsom" treatment and can be used to measure the potential rate of SOM decline.

C1: Cropped - Residues retained (Machanga only).

The land was cleared as for F2. Each season, sorghum is grown without manure or fertilizer. Weeding, pesticide and fungicide applications are done according to the current practice. After harvest, the stovers are cut and left on the plot.

C2: Cropped - Extra residues.

Sorghum is grown each season as for C1. After harvest, the stovers are left on the plot, adding all the stovers from the C3 plot in the same replicate block.

C3: Cropped - Residues removed.

Sorghum is grown as for C1. After harvest, the stovers are cut and removed to the C2 plot in the same replicate block. Since the C3 plots are twice the size of the C2, plots, the C2 plots get three times the rate of residues in C1.

F1P/F2P/C1P/C2P/C3P; (Machanga only).

These are treated the same as the corresponding treatments F1-C3, apart from an initial application of 250 kg P ha^{-1} as TSP fertilizer in March 1994 only. (Therefore, for these plots, the stovers from plot C3P are added to plot C2P in the same replicate block.)

At Mutuobare, the area available was smaller and the soil is naturally well supplied with P so there was no need for the fertilizer treatments. The treatments are: Bush, F1, F2, C2 and C3, in three replicate blocks.

4.3 Results

So far, the main contribution of the experiment to the project objectives has been as the place where the intensive monitoring of soil mineral N dynamics was done, because it included the bare fallow treatment (Project Summary Paper 5). Soil nitrate and crop growth data were also used to develop the soil N turnover submodel for the PARCH crop growth model, but at present, no publication is available. It can be mentioned that the choice of turnover time for short-period SOM-N pools (turnover time in months) was important to account correctly for the differences between Machanga and Mutuobare soils.

At the time of the project workshop, the complete agronomy data had not been assessed for trends. However, the effect of P fertilizer was very clear in relieving P deficiency. It appears that so far, the extra residues in treatment C2 have little effect on yields. The current lifetime of nearly four years is unlikely to be long enough to give detectable differences in SOM-C, based on experience in Trial 1, where manure was used. Manure is much more effective at increasing SOM than undecomposed crop residues. Model predictions have been made, but not yet tested against field results.

4.4 References and reports: SOM

GP Warren, SS Atwal and JW Irungu. 1997. Soil nitrate variations under grass, sorghum and bare fallow in semi-arid Kenya. Experimental Agriculture 33: 321-333.

GP Warren 1995. Effects of P and crop residues on Soil Organic Matter, N and P balances and Soil Mineral N in Lower Embu, Kenya. Proceedings of the 5th TSBF African Network Workshop, Entebbe, Uganda, 15-20 May 1995. Tropical Soil Biology and Fertility Programme, Nairobi, Kenya.

GP Warren and JA Meredith 1998. Isotopic composition of organic carbon in some soils of semi-arid Africa. In: Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems. (Eds: L Bergstrom and H Kirchmann). pp 23-32. CABI, Wallingford, U.K.

GP Warren 1998. Effects of native soil phosphorus on biodiversity, productivity and the dynamics of soil carbon and nitrogen at two sites in semi-arid Kenya. Symposium No. 12. Proceedings of the 16th International Congress of Soil Science, Montpellier, France; 19-26 August 1998.

5. On-farm work with DAREP

5.1 Diagnostic survey on-farm

Soil C, N, P and K varied substantially between sites (Project Summary Paper 3). To relate this observation more closely to the on-farm situation, soil from farmers' fields was analysed. Diagnostic surveys were to be carried out by DAREP teams, and the first was done in Tharaka-Nithi District. As part of this survey farmers were asked to identify fertile and infertile fields on their farms and the soils were sampled. These samples were analysed by the Soil Fertility Project. Soil fertility was variable between farms and between fields, and soil organic C was the soil property correlated most closely with farmers' perception of fertility (Irungu et al. 1997a). Extractable P also varied widely and this formed the scientific starting point for further work mentioned below.

5.2 N fixation by cowpeas

Legumes can supply at least some of their N requirement by fixation from the atmosphere, but P must be supplied from the soil. Soil P varied greatly between farms, and especially between Machanga and Mutuobare sites. These observations suggested that the effectiveness of N fixation by legumes should be assessed in relation to soil P in the area. A separate project has been funded by DFID, forming the PhD project for JW Irungu, KARI agronomist. An initial survey of 50 farms showed that legumes are widely grown in the area, but very little fertilizer is used, so their performance depends highly on soil P (Irungu et al. 1997b). Following this, on-farm field experiments were set up to assess N fixation by cowpeas at four farms of contrasting fertility with respect to P, in the 1996-7 seasons, collaborating with the Soil Fertility Project. The results will be reported next year.

5.3 References and reports: On-farm.

JW Irungu, AN Micheni, A Sutherland and GP Warren 1997a. An appraisal of soil fertility in smallholder farms in the semi-arid areas of Tharaka-Nithi District: framers' assessment compared to laboratory analysis. In: Kangara, J., Sutherland, A. and Gethi, M. (Eds) Proceedings of the Conference on Participatory Dryland Agricultural Research east of Mount Kenya, January 21-24, 1997. KARI: Kitale, Kenya. pp 243-248.

JW Irungu, GP Warren, M Wood and JR Okalebo 1997b. Soil fertility management practices in smallholder farms in semi-arid Mbeere in eastern Kenya: an analysis of the farming systems. In: Kangara, J., Sutherland, A. and Gethi, M. (Eds) Proceedings of the Conference on Participatory Dryland Agricultural Research east of Mount Kenya, January 21-24, 1997. KARI: Kitale, Kenya. pp 214-229.

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EFFECTS OF CONTINUOUS MANURE APPLICATION ON GRAIN YIELDS AT THE SEVEN SITES OF TRIAL 1, FROM 1993 TO 1996.

1. Introduction and objectives

In the first phase from 1989 to 1993, both crop yields (Gibberd, 1995) and soil fertility (Warren et al., 1997) were increased significantly by using manure. After this initial increase in soil fertility, the productivity of the land from 1993 to 1996 was expected to stabilise at different levels in the three treatments. The yields should thus be more representative of long-term cropping at the differnt manure rates. A new statistical treatment devised to investigate differences between the sites. These differences are largely controlled by the soil, since the same manure was used everywhere.

2. Data work-up

2.1 Yield response calculations and ranked lists

The main interest was in the effects of adding manure, so the responses calculated as follows (the treatments with 0, 5 and 10 t ha^{-1} manure were coded M0, M2 and M1 respectively, see Appendix 1:

(i) The response to the first 5 t ha^{-1} manure (treatment difference M2-M0)

(ii) The response to an additional 5 t ha^{-1} manure (treatment difference M1-M2)

For each site there were three replicates and the mean responses and associated Standard Errors were calculated. Then the sites were ranked: the best response at the top of the list. Since the individual SEs did not vary excessively, a pooled SE was calculated for each list, and also the Least Significant Difference (P=0.05, DF=12) for a comparison between two soils.

The lists were then examined to identify the sites which tended to give particularly good and poor responses to manure. The yields, responses and rankings will vary from season to season with the weather, management variations etc. However, the soils are always the same, so effects of soil fertility should show through as tendencies to above- or below-average responses, even though the effect might be masked in a particular season. Sometimes, there were apparent negative responses. Manure at the rates of this experiment is unlikely to depress crop yield, so these negative responses are merely a result of random variation. Normally, negative responses were not significantly different from zero. In these lists, a group of sites was formed from the bottom upwards, identifying a group of sites where the response differed little from zero.

3. Results

3.1 Overview of response curves

The cumulative yield response over all crops (cereals plus legumes for every season) was plotted against manure rate (Figure 1). The response to manure was highest at Machanga. In general, the response to the second 5 t ha^{-1} of manure was be less than the response to the first 5 t ha^{-1}, as would be expected. At Gategi, there was little response to the low manure rate, but a high response to extra manure. At Kajiampau, the response line was linear. These observations suggested that Machanga, Gategi and Kajiampau were sites where the response to manure differed from the response at the other sites.

3.2 Results: crops.

Results for sorghum (Table 1) are described in detail: for the other crops the main results are summarised.

3.2.1 Sorghum.

Sorghum yield is considered to be the best test of soil fertility because it gave higher yields than any other of the four crops, except at Kajiampau. The ranking lists for sorghum showed the close consistency between the seasons with Machanga at the top and Gategi at the bottom. In all seasons, the first 5 t ha^{-1} manure resulted in a significantly greater response at Machanga than at Gategi. Most sites fell between in a fairly clear group. Manure response at Machanga was above the central group in two seasons, and manure response at Gategi was below the central group in two seasons. It was concluded that for the first increment of manure, Machanga gave a high response and Gategi gave a low response. This result confirmed the hypothesis proposed above (section 3.1) that Machanga and Gategi differed from the other sites. The other soils gave an intermediate response, but differed little between themselves.

For the second increment of manure, the response to manure did not differ significantly between sites, either with or without any of the three "exceptional" sites mentioned at section 3.1.

3.2.2 Millet.

There were significant differences between top and bottom sites in most lists for millet, but the results were not nearly as consistent as for sorghum. For the low manure rate, there were some responses to manure at Machanga, Kamwaa and Gacheraka in the wetter seasons. In the dry 4/96 season (only 261 mm rainfall, the driest of any season), no differences between sites were significant, indicating major limitations by low water availability.

For most sites, the responses to extra manure were fairly evenly distributed around zero, indicating no overall effect. But Gategi and Kajiampau appeared to give high responses even though there was little effect of the low rate.

3.2.3 Green Grams

Little attention need be paid to the results for green grams because they contributed little to the grain production. There were small responses in the wetter seasons.

3.2.4 Cowpeas

The lists for cowpeas showed complicated variations between seasons. It is felt that the response of legumes to the manure is complicated because of their secondary role in the intercropped system, where they are literally overshadowed by the cereal component. This may inhibit responses in otherwise favourable seasons. No one site was consistently much better or worse than the majority. It was considered that cowpeas responded to manure in the wet seasons, but not much in the dry seasons.

The growth of cowpeas at Kajiampau merits special attention. Kajiampau gave the best yield responses for legumes overall, and at this site only, cowpeas were the highest yielding crop. Conditions here evidently favoured cowpeas and it was observed that the balance of competition between cereal and legume components of the cropping system varied between sites and was not much affected by manure application (see also Appendix 8).

3.3 Ranking of sites and soils

As an indicator of which sites gave consistently good responses to manure, the frequencies with which each site appeared in the top two ("high") and bottom two ("low") places of each list were counted (Table 2). The table is not truly independent of the LSD comparisons since it is derived from the same data, but it is a complementary approach to assist interpretation.

First 5 t ha^{-1} manure. Machanga, Kamwaa were often found in the top two places of the lists and rarely in the bottom places (Table 2) while Gategi and Mutuobare were often found in the bottom two places. Thus, the lists indicate that Machanga and Kamwaa had poor soil fertility because relatively large responses were common.

Extra manure. Compared to the results for the low manure rate, more variety of sites appeared in high and low response categories. Gategi, Machanga and Kajiampau appeared most often in the top two, while in the bottom two places, all the sites appeared about equally often (except for the responsive Machanga and Kajiampau sites). The rankings were therefore less consistent. It appears that after relief of the most severe nutrient deficiencies, responses to extra manure were similar in the sites, hence the more random ranking in the lists. Gategi site was unusual because it gave few responses for the first 5 t ha^{-1}, but more for the extra manure.

In conclusion, Machanga and Gategi were clearly identified as giving exceptional responses.

Machanga gave frequent and significantly high responses to both 5 t ha^{-1} and extra manure. Gategi gave significantly low responses to 5 t ha^{-1} manure but some significantly high responses to extra manure. Kajiampau was added to the list of unusual sites because it gave some unusually high responses in cowpeas and millet to extra manure.

For the other four sites, some gave significantly high responses with particular crops and seasons, notably with legumes at Kamwaa. However, they fell into a statistically similar group for much of the time. An important additional lesson from this is that reliance cannot be placed on results for a single season, which is likely to be unusual in some way.

3.4 Seasonal differences in manure response

There was a suggestion that responses were lower in drier seasons. With intercropping, ratio between the cereal and legume components could also depend on the weather, with wet weather favouring cereals.

4 Response to manure in relation to soil properties

The responses to manure could differ between places because the different soils had different amounts of available nutrients. An objective of soil analysis is to help predict nutrient requirements from measurements of soil. Statistical consideration of the agronomic results showed that at three sites, the responses to continuous manure were different from the response at the other group of four sites: the group of four were treated together.

4.1 Gategi

Gategi soil was the only vertisol and it showed an anomalous response curve, where the response to the second increment of manure was less than the response to the first 5 t ha^{-1}. Two possible explanations may be proposed. First, the high clay content means that a higher proportion of the nutrients supplied at the low rate of manure may be made unavailable on the high surface area of clays or in organic matter stabilised by the clay. At the higher rate, more nutrients would be surplus to soil capacity and instead available for plants. However, the montmorillonitic clays of vertisols are not normally associated with this kind of nutrient immobilisation. The second suggestion is that a high proportion of the low rate of manure may have fallen to the bottom of the deep cracks formed in the dry seasons, and become inaccessible. However, this behaviour should result in very variable responses because the exact response would be determined by the chance formation of cracks, and the low response to the first 5 t ha^{-1} manure at Gategi was rather consistent.

4.2 Machanga

Machanga soil was the most deficient in phosphorus as indicated by extractable P (Olsen-P = 0.9 mg

kg^{-1}). At the nearby SOM experiment on almost the same soil, addition of P fertilizer alone caused sorghum grain yield to be almost tripled (Warren et al. 1997). It is clear that extreme P deficiency is the cause of the different response characteristic here. Analyses of the manure from 1993 to 1996 showed that on average, 24 kg P ha^{-1} were supplied each year in 5 t ha^{-1} manure, which alleviated the deficiency.

4.3 Kajiampau

There was no extreme soil chemical characteristic at Kajiampau , although the Olsen-P was high (10 mg kg^{-1}) whereas total N (0.051%) was the lowest of any soil, so imbalance of N and P may be a factor here. The good performance of legumes relative to cereals could be explained by this, since although the soil is probably deficient in N, the legumes can fix their own effectively because P is not limiting.

4.4 Mutuobare, Kamwaa, Gacheraka and Kaanyaga

This group of soils gave statistically similar responses, and the response to the first addition of manure was investigated in relation to soil N and P. The soils look fairly similar, being sandy loams, reddish in colour and are provisionally classed as chromic cambisols.

Simple correlations were made between the size of the response to 5 t ha^{-1} manure for each site and (i) the mean soil total N (Kjeldahl method) and (ii) extractable P (Olsen method), in the unmanured soil. The agronomy data were the cumulative yields of legumes, cereals and total grains over the three years from the 11/93 season to the 4/96 season. The soil data were for soil sampled in all plots at all sites in 2/93, at the start of the project. It is obvious that not too much reliance can be placed on these results because they are over four points only, although the data points are themselves representative means over many measurements (plots and seasons). A significant inverse relationship was found between the response in total grains response and soil total N (Figure 2). This suggested that the crops were responding mainly to N in the manure, because the higher the soil N, the less the response to manure. A further examination was made by correlating the responses in legume and cereals separately. The correlation coefficients were significant ($P = 0.05$) only between legumes and Olsen P and between cereals and N, suggesting that legumes responded to P and the cereals to the N. This seems logical since legumes can fix their own supply of N (if P is adequate), but cereals dominated the overall yields and responses.

Figure 1. Response in total cumulative grain yield (3 years, all crops) to continuous manure, at the seven sites of Trial 1..

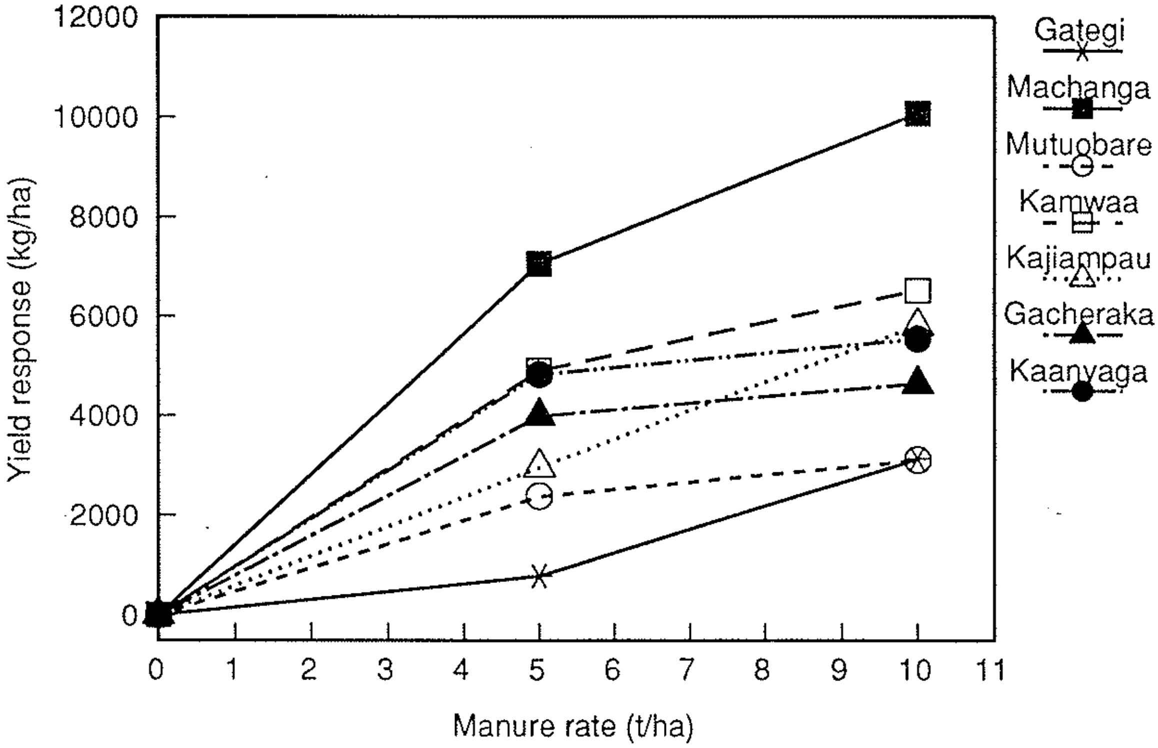


Figure 2. Response in cumulative grain yield to 5 t/ha continuous manure in relation to total N in unmanured soil.

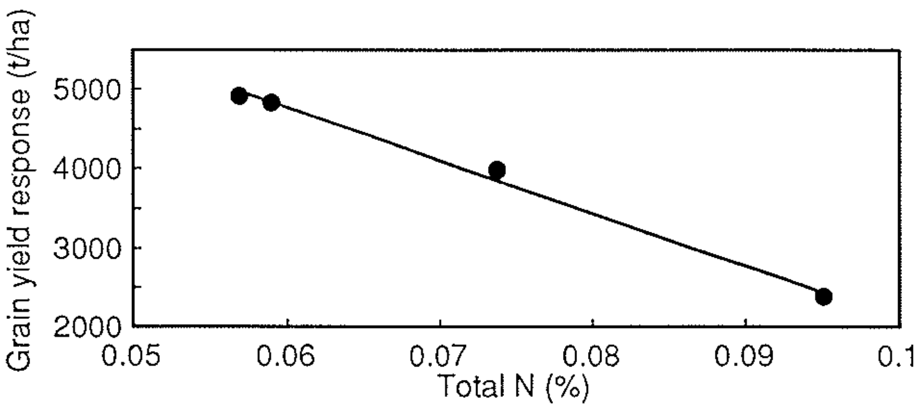


Table 1. *Responses in grain yield (kg ha^{-1}) for sorghum (intercropped with cowpea) as a result of annual manure application, with sites placed in ranked order of the size of the response. Standard Errors are shown for the mean response at each site, with a pooled SE for all sites and an LSD for comparing two site means.*

Response to the first 5 t ha^{-1} manure (with Standard Error)

	11/93 season		11/94 season		11/95 season
Mac	1033 (187)	Mac	2793 (181)	Mac	1187 (209) a
Kam	373 (114) a	Kny	1227 (13) a	Kny	1160 (208) a
Gch	373 (167) a	Mut	1147 (141) a	Mut	907 (192) a
Kaj	280 (266) a	Kaj	853 (207) a	Kaj	760 (284) a
Kny	213 (373) a	Gch	653 (48) a	Gch	653 (104) a
Mut	13 (361) a	Kam	613 (173) a	Kam	613 (359) a
Gat	-133 (87) a	Gat	293 (674)	Gat	-67 (104)
Pooled SE:	(246)		(289)		(225)
LSD (5%)	759		889		694

Response to an additional 5 t ha^{-1} manure (with Standard Error)

	11/93 season		11/94 season		11/95 season
Mac	747 (306) a	Kam	1053 (292) a	Mac	520 (312) a
Kny	387 (275) a	Mac	740 (612) a	Gat	400 (288) a
Mut	360 (349) a	Gat	640 (572) a	Kny	213 (298) a
Kaj	347 (254) a	Mut	587 (170) a	Gch	173 (176) a
Kam	253 (93) a	Kaj	440 (401) a	Kaj	67 (213) a
Gch	160 (92) a	Gch	107 (58) a	Mut	53 (260) a
Gat	80 (174) a	Kny	-67 (127) a	Kam	-227 (577) a
Pooled SE:	(240)		(377)		(327)
LSD (5%)	740		1163		1007

Notes: Abbreviations for site names: Gat: Gategi, Mac: Machanga, Mut: Mutuobare, Kam: Kamwaa, Kaj: Kajiampau, Gch: Gacheraka, Kny: Kaanyaga.

Statistically similar groupings: For each list, multiple t-tests were used to form the largest (i.e. with most sites) group without significant differences at the 5% level, and these are indicated by the symbol a.

Table 2. *Frequency of sites at the top and bottom of the ranking lists for individual crops (sorghum, cowpea, millet and green gram) and seasons (11/93, 4/94, 11/94, 4/95, 11/95, 4/96).*

(i) Response to the low rate of manure

	Top two places	Bottom two places
Gategi	1	8
Machanga	7	2
Mutuobare	2	6
Kamwaa	8	2
Kajiampau	0	4
Gacheraka	2	1
Kaanyaga	4	1

(ii) Response to the second increment of manure

	Top two places	Bottom two places
Gategi	5	4
Machanga	7	1
Mutuobare	1	5
Kamwaa	2	5
Kajiampau	6	0
Gacheraka	0	5
Kaanyaga	3	4

RESIDUAL VALUE OF MANURE IN TRIAL 1

Introduction

Manures and fertilizers can have significant residual effects: increases in crop yields occurring in seasons after the one in which the manure or fertilizer is applied. To assess the full benefits of fertility improvements, account should be taken of the residual effect and how long it lasts. As described above (Appendix 1), Trial 1 was started in 1988/9 and by 1993, one of the original objectives, to compare intercropped and sole cropped rotations, was considered to be completed. Instead of continuing that comparison, it was decided to assess the residual effects of manure. The design was therefore altered to investigate the residual effects of manure by stopping manure application in some plots.

Treatments

Sorghum/cowpea were planted as an intercrop every October (Seasons 1, 3 & 5) while millet/green gram intercrop was planted every March (Seasons 2, 4 & 6). This rotation was applied to both the Continuous manure treatments and Residual manure treatments. The fertility treatments were as follows:

Continuous Manure

- No manure (control) (code C3M0)
- 5 t ha^{-1} manure annually (code C3M2)
- 10 t ha^{-1} manure annually (code C3M1)

Residual Manure

- 5 t ha^{-1} annually, October 1989 to 1992 only (code C3R2)
- 10 t ha^{-1} annually, October 1989 to 1992 only (code C3R1)

Since 1989, all manure was obtained from the Ministry of Agriculture's Goat and Sheep Project station at Marimanti. Continuous manure plots have received annual manure since the start of the experiment in 1988 and 1989. The plots for the Residual manure treatment last received manure in October 1992, so the comparison of residual and continuous effects starts from October 1993.

The Residual plots were adapted from plots of the previous sole crop rotation (code C1) which had legumes planted in October and cereals in March, rather than the same intercropped rotation. However, analyses of variance on the measurements of soil organic C, total N and extractable P in 1993 showed that there were no significant differences between the sole crop and intercrop rotations in soil properties. Thus a reasonable comparison of continuous and residual manure is possible.

Results: residual effects of manure.

Cumulative yield response Analyses of variance for the five treatments were done for each site, and the pattern of responses was similar at all sites, so only an all-sites mean was used for this paper. During the three years after manure application ceased, residual manure gave significantly more grain (approximately 240 kg ha^{-1} of legumes and 1190 kg ha^{-1} of cereals) than the control (Fig. 1). The residual effect of 10 t ha^{-1} manure was no larger than the effect from 5 t ha^{-1}.

Season-to-season results Residues of 10 t ha^{-1} gave significant yield responses in seasons 1 and 3 (10/93 and 10/94 planting; Fig. 2). Responses were not significant at the March planting seasons. The reasons are probably a combination of (i) the lower responsiveness of the millet/gram crop combination, compared to the sorghum/cowpea combination (Gibberd, 1995) and (ii) the lower responses to manure apparant in drier seasons (Appendix 2).

Residual Value

To compensate for season-to-season variations in the yields and residual effects, a **residual value** was calculated, relative to the yield under continuous manure as follows:

$$\text{Residual value} = \frac{\text{Response for residual manure treatment}}{\text{Response for continuous manure treatment}}$$

The residual value of the 10 t ha^{-1} treatment showed a progressive decline (Fig. 3), although the residual value in the 5 t ha^{-1} treatment fluctuated, especially for seasons 3 and 4. For both rates, the residual value became negligible in the last season.

Conclusions

Figure 3 suggests that the residual value remained noticeable up to season 5 (10/95 planting), i.e. 7 seasons and about 3.5 years after manure application. Economic and adaptive studies of manure use need to take this into account when planning experiments with manure in order to obtain a full assessment of the benefits.

Figure 1. Residual effects of manure application: cumulative yields for 6 seasons from 10/93 to 7/96, averaged over all sites.

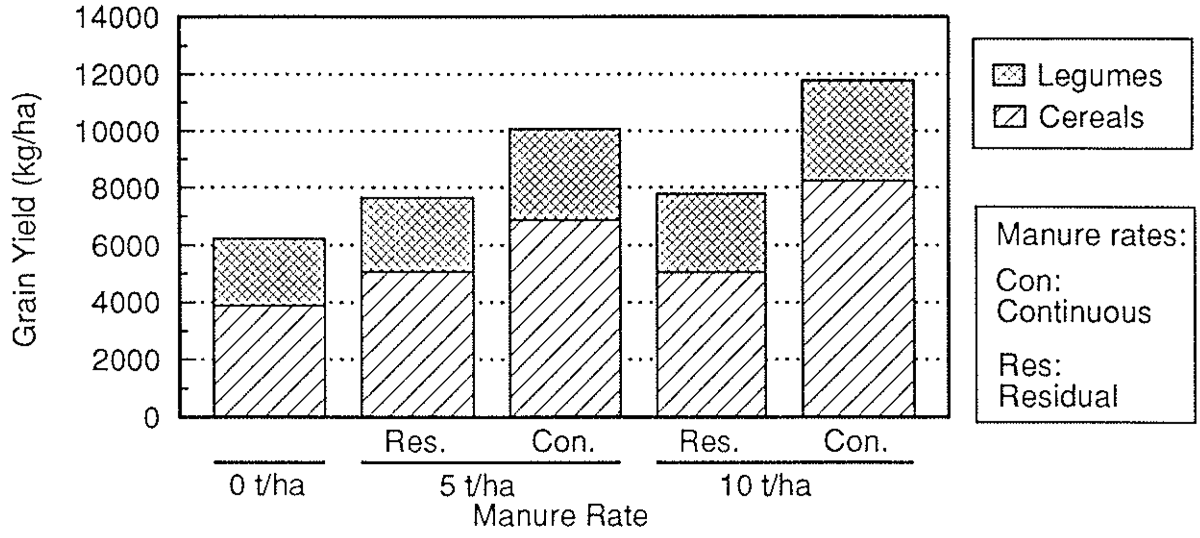


Figure 2. Effect of residues of 10 t/ha manure applied from 1988 to 1992, on yields from 1994 to 1996.

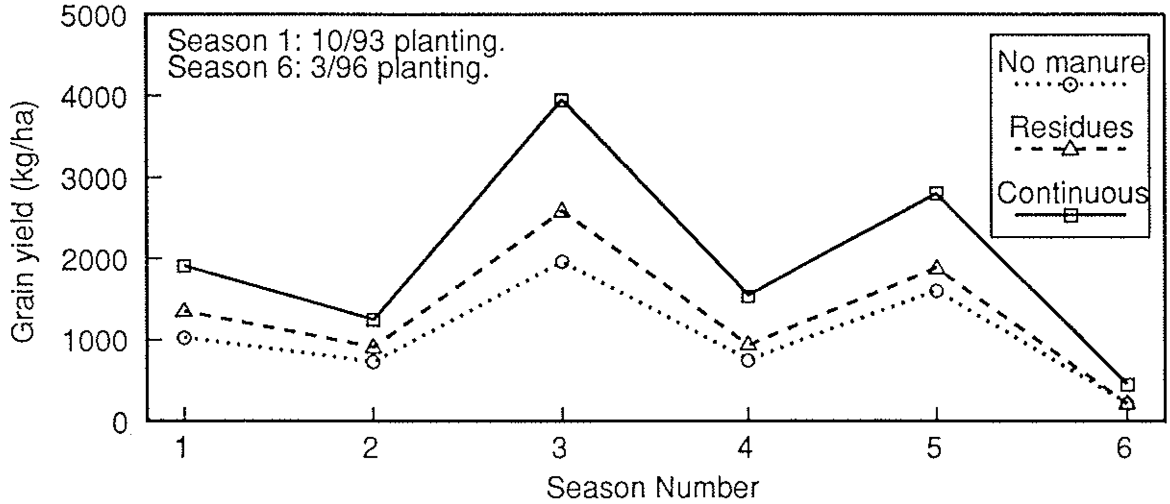
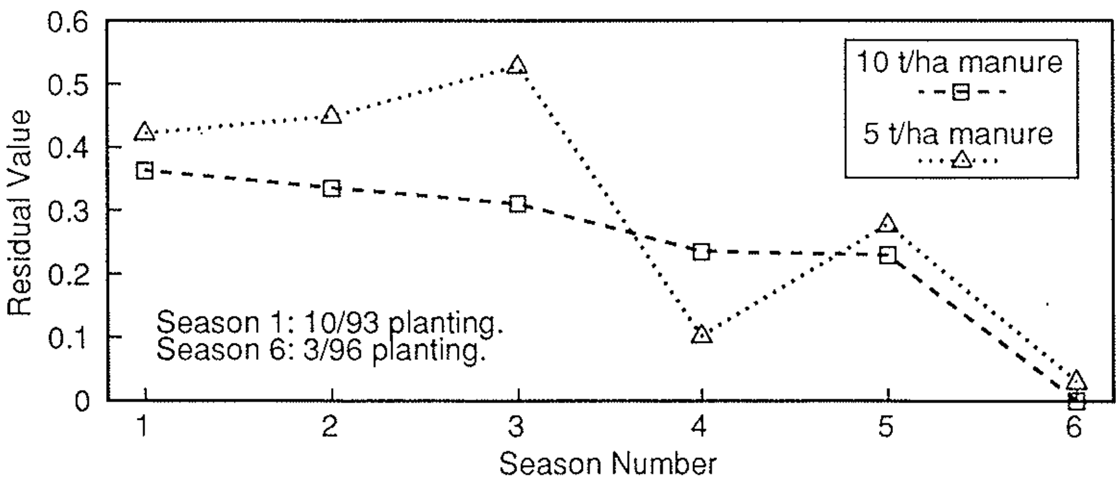


Figure 3. Residual value of manure (applied 1988 to 1992), in 1994 to 1996. Residual Value is calculated relative to the response to Continuous manure.



SOIL FERTILITY IMPROVEMENTS UNDER MANURING FROM 1988 TO 1993 IN TRIAL 1.

Introduction

Low soil fertility is a serious environmental limitation to agricultural development in the present economic climate, because of the high cost of fertilizers. For most farmers in Kenyan semi-arid climates, manure is the only affordable concentrated source of plant nutrients. To sustain or improve production, good management of manure is essential. This paper looks at the effects of manure on fertility in the soils of Trial 1, as a background to the changes measured in the following four years.

Materials and methods

Field experiment In 1988/9, Trial 1 was set up to test the effects of goat manure and crop rotation systems as described above (Appendix 1). Agronomic results from the start to 1993 were reported by Gibberd (1995). The manure treatments were:

(M0) Control (no manure).

(M1) High manure rate: 10 t ha^{-1} annually applied in October.

(M2) Low manure rate: 5 t ha^{-1} in October for most years.

From October 1989, all manure came from the Ministry of Agriculture station at Marimanti, Tharaka-Nithi. This very important feature of the experiment means that differences between sites in the amounts of nutrients found are largely due to differences in the nature of the soils, and are not due to the variable nature of locally acquired manure. The total amounts of Marimanti manure used before 1993 were 40 t ha^{-1} (high rate) and 20 t ha^{-1} (low rate) for all sites except Kirimbu (30 and 15 t ha^{-1}). Due to a change in plans, an extra 10 t ha^{-1} of local manure was applied in the first year at some sites. However, this appeared to have little effect on soil properties four years later. It will be seen that the effects of manure were related to the Marimanti manure applied.

The plots were cropped to rotations with sorghum, cowpea, millet and green gram, as sole crops and as intercrops as detailed by Gibberd (1995). The amounts of residues and grains increased in this order of the cropping systems: (i) Sole crop, cereal planted in March < (ii) Sole crop, cereal planted in October < (iii) Intercropped system. This suggested that fertility differences might arise, because the higher yielding cropping systems might deplete the soil nutrients faster, but also gave higher returns of C to the soil. However, there were no significant differences between the cropping systems in soil chemical measurements. Therefore the results presented are for the effects of manure, meaned over all cropping systems.

Soil sampling and analytical methods Early in 1993, all plots at all sites (243 plots) were sampled to 20 cm. The soil was air-dried and ground to pass a 2mm sieve. Measurements were made of extractable P (Olsen's method, 0.5M $NaHCO_3$), exchangeable K, total soil N (Kjeldahl method) and organic C (Tinsley method). The methods used normally conform to those of the Tropical Soil Biology and Fertility Programme (Okalebo et al. 1993).

Results: Differences between sites in unmanured soil

Unmanured Gategi soil differs from the others, as it is a vertisol and has the highest pH, clay, exchangeable cations and organic-C (Table 1). The other soils fall into mapping units where chromic cambisols and ferralic arenosols predominate (Kenya Soil Survey, 1982). All soils have a neutral pH. Exchangeable cations were low (<10 cmol kg^{-1}) at Machang'a, Kaaragankuru and Kirimbu.

Wide variations between sites may be noted for extractable P (0.94 to 30.97 mg kg^{-1}, Figure 1). Extractable P was low at many sites, but P sorption was never high (<150 mg kg^{-1}). None of the soils had received fertilizer before the start of the experiment, so the high concentrations of Olsen-P (>30 mg kg^{-1}) found at Mutuobare (Figure 1) were surprising. This was attributed to the local geology, since the P mineral apatite was identified in the soil fine sand fraction (Plum 1994). Kajiampau site was also naturally well supplied with P (10.8 mg kg^{-1}, Table 1).

Machanga and Mutuobare soils were naturally well-supplied with K, having over 250 mg kg^{-1} of exchangeable K (Table 1). As with P, wide variations between sites are evident for exchangeable K (29 to 331 mg kg^{-1}, Figure 2). Five sites appeared to be low in K, having less than 60 mg kg^{-1} of exchangeable K: Gategi, Kamwaa, Kajiampau, Gacheraka and Kaanyaga, although only Kaanyaga appeared to be seriously deficient.

N in the unmanured soil (0.045 to 0.095%, Table 1) was always less than 0.1%, which is often regarded as low for arable cropping. However, the range suggests that the amount of available N is likely to vary between soils, since a roughly constant proportion (1-3%) of soil organic N is mineralised in each growing season.

Effects of manure

Composition of manure Analyses of Marimanti manure were carried out from 1993 to 1996. The feeding of the Marimanti goats was unchanged from 1989 to 1996. Assumimg that the composition of the manure was also unchanged, it was estimated that 1281, 102, 24 and 138 kg ha^{-1} of C, N, P and K respectively were applied each year in Marimanti manure at the low rate of application (5 t ha^{-1}), and double these amounts in the high manure rate.

Phosphorus. Addition of manure always caused highly significant increases in Olsen-P (Figure 1). Larger increases in Olsen-P were found at the sites with more natural P. For example, compare Machanga and Mutuobare sites. Averaged over all sites, the increase in Olsen-P was roughly proportional to the rate of Marimanti manure applied, since the annual low rate was 5 t ha^{-1} and the high rate 10 t ha^{-1}.

Potassium. Manure almost always gave highly significant increases in exchangeable K (Figure 2). The exception was Kamwaa, where the soil is quite sandy. Leaching loss may be significant here. On average, the increase in K was roughly proportional to the rate of manure application.

Nitrogen. Five of the nine sites showed significant increases in soil total N after manuring (Figure 3). Normally, there was no significant difference between the low and high manure rates in total N, indicating that the higher rate of manure conferred no additional benefit on soil N supply.

Carbon. SOM, assessed by organic C varied substantially between sites (Figure 4). As expected, organic C and total N showed similar patterns in amount and significance of the response (Table 2), since most soil N is contained in soil organic matter. The largest increases in organic C with manure were found at Gategi, Machanga, Mutuobare and Kaaragankuru sites. Manure had little effect at Kirimbu. The high rate of manure normally resulted in only a little more soil organic matter than the low manure rate, an increase that was significant onlt at Machanga.

Calcium and magnesium. There was little effect of manure on exchangeable Ca and Mg (Figs 5 and 6), although at Machanga and Kaaragankuru, the two sites with the lowest Ca and Mg, significant increases were found.

Discussion

P and K concentrations varied widely between sites, indicating that nutrient requirements can vary a lot within the region. The response to manure may be due to different elements in different places. Nutrient build-up was highest at the sites with most natural P and K. Thus, where soil P and K supplies are good in semi-arid soils, surplus nutrients are retained. Nutrients can build up to high concentrations where there are no offtakes, as found under cattle bomas by Probert et al. (1995).

The build up of soil organic matter by manure varied between the sites, but was not related to the original soil C. At Kirimbu, C was not increased, but the significant increases in P and K prove that manure was not lost by erosion. We suggest that organic matter is more quickly decomposed here. Kirimbu is hotter than the other sites, with a mean annual maximum temperature of 35°, compared to 29° to 33° at the others.

Conclusions

There were wide variations between sites in natural fertility. Strategies for integrated nutrient management (INM) and adaptive development in semi-arid arid areas need to recognise that the limiting nutrient, and thus INM strategy may well be different between farms and fields.

The low manure rate normally increased C and N, but the high rate was ineffective at increasing C and N over the low rate and the extra N was therefore lost. It follows that the most efficient way to use manure N is to spread a low rate over a wide area. This obviously requires more labour than adding a high rate to a small area. But since fertility maintenance is an increasing constraint, the additional work may become essential for sustainability.

References

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Okalebo, JR., Gathua, KW. and Woomer, PL. 1993. Laboratory methods of soil and plant analysis: A working manual. Tropical Soil Biology and Fertility Programme. Marvel EPZ (Kenya) Ltd., Nairobi.

Probert, ME., Okalebo, JR. and Jones, RK. 1995. The use of manure on smallholders' farms in semi-arid Eastern Kenya. Experimental Agriculture 31: 371-381.

Appendix 4, Table 1. Properties of the unmanured soils in the original nine sites of Trial 1.

	Gategi	Machanga	Mutuobare	Kamwaa	Kajiampau	Gacheraka	Kaanyaga	Kaaragankuru	Kirimbu
pH (water)	8.2	6.55	6.84	7.81	7.1	7.54	7.09	6.96	6.86
pH ($CaCl_2$)	7.25	5.75	6.18	7.08	6.39	6.85	6.34	6.14	6.27
Exchangeable bases (cmol kg^{-1}) [Σ Na,Mg,K,Ca]	54.4	6.1	10.3	13.9	12.0	19.7	12.8	4.2	9.0
Organic C (%)	1.313	0.61	0.948	0.507	0.561	0.706	0.611	0.433	0.363
Total N (%)	0.078	0.06	0.095	0.057	0.051	0.074	0.059	0.045	0.050
Olsen-P (mg kg^{-1})	1.76	0.94	30.97	3.4	10.8	1.96	6.03	1.77	5.40
Exch-K (mg kg^{-1})	49	331	285	46.2	55.2	47	29	132	120
P sorption: SPR[a]	149	94	2.7	44	16	88	129	32	28
Sand (%)	24.1	56.5	59.1	60.8	65.1	52.5	48.1	70.1	65.5
Silt (%)	22.1	12.7	15.1	13.4	16.8	17.7	11.8	13.1	18.4
Clay (%)	53.8	30.8	25.8	25.8	18.1	29.8	40.1	16.8	26.1
Texture	Clay	SCL	SCL	SCL	SL	SCL	SC	SL	SCL
Annual rainfall (mm), 1988-1992	910	805	867	881	1148	1118	1065	1005	731

[a] Standard Phosphorus Requirement; P sorbed (mg kg^{-1}) at a solution concentration of 0.2 mg P l^{-1}
SCL = Sandy Clay Loam; SL = Sandy Loam; SC = Sandy Clay

Appendix 4; Table 2. Levels of statistical significance for the increases in soil extractable P, exchangeable K, total N, organic C, and exchangeable Ca and Mg, which resulted from application of manure at the nine sites.

(i) Effect of the low rate of manure (5 t ha^{-1} per year).

Site	P	K	N	C	Ca	Mg
Gategi	***	***	***	**	NS	NS
Machanga	*	**	***	NS	*	NS
Mutuobare	NS	***	**	**	NS	NS
Kamwaa	***	NS	NS	*	NS	NS
Kajiampau	*	**	*	NS	NS	NS
Gacheraka	*	NS	NS	NS	NS	NS
Kaanyaga	NS	***	*	NS	NS	NS
Kaaragankuru	***	***	***	***	***	**
Kirimbu	NS	**	NS	NS	NS	NS

*, ** and *** denote increases significant at the 5, 1 and 0.1% levels respectively.

(ii) Effect of increasing the manure rate from 5 to 10 t ha^{-1} per year.

Site	P	K	N	C	Ca	Mg
Gategi	NS	NS	NS	NS	NS	NS
Machanga	***	*	NS	*	*	*
Mutuobare	***	***	NS	NS	NS	NS
Kamwaa	NS	NS	NS	NS	NS	NS
Kajiampau	**	***	NS	NS	NS	NS
Gacheraka	**	**	NS	NS	NS	NS
Kaanyaga	**	NS	NS	NS	NS	NS
Kaaragankuru	NS	***	NS	NS	NS	NS
Kirimbu	*	**	NS	NS	NS	NS

*, ** and *** denote increases significant at the 5, 1 and 0.1% levels respectively.

Figure 1. Effects of manure on extractable soil P.

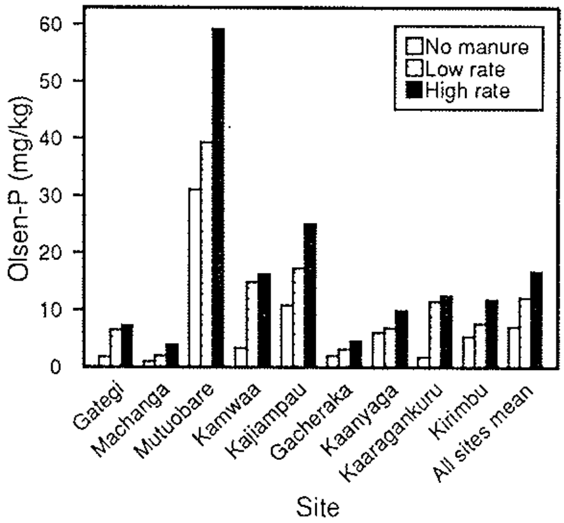


Figure 2. Effects of manure on exchangeable soil K.

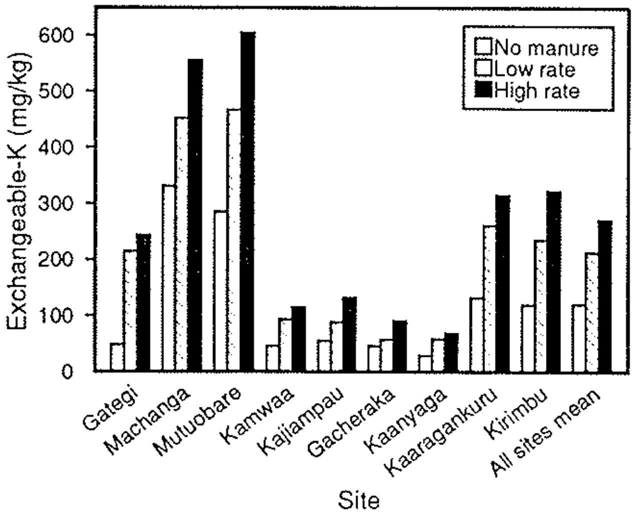


Figure 3. Effects of manure on soil total N.

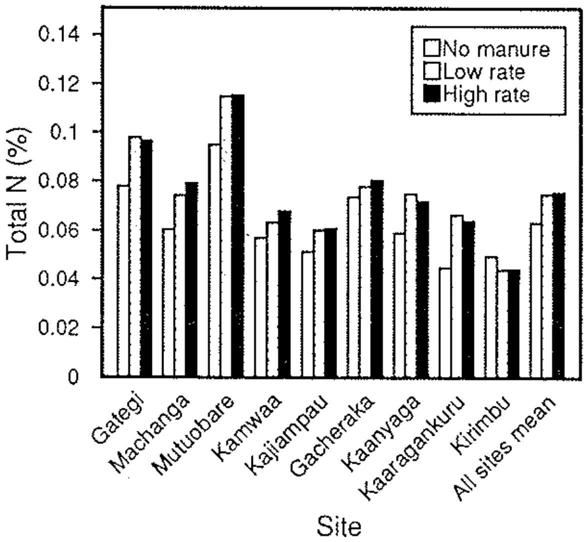


Figure 4. Effects of manure on soil organic C.

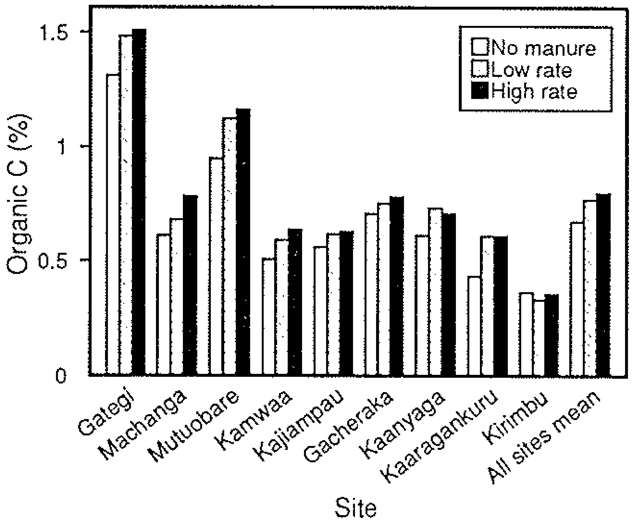


Figure 5. Effects of manure on exchangeable soil Ca.

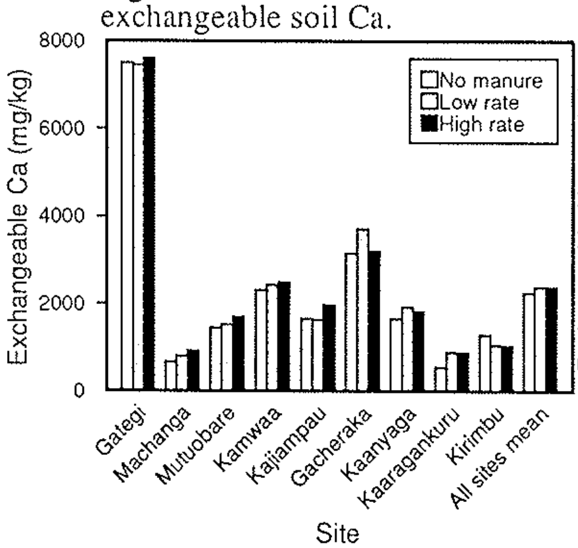
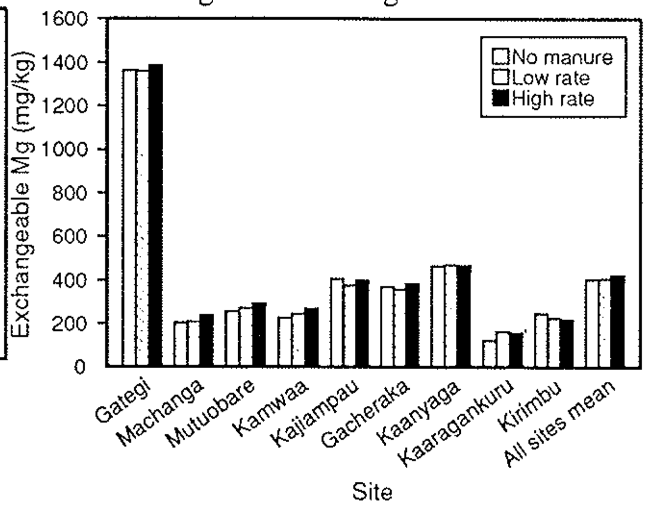


Figure 6. Effects of manure on exchangeable soil Mg.



DYNAMICS OF SOM CARBON IN TRIAL 1.

Introduction

The principal scientific objective of the Project (Appendix 1) was to test the established Rothamsted carbon turnover model ROTHC-26.3 (Coleman and Jenkinson, 1996) for soils of the semi-arid tropics. The model describes the dynamics of soil organic carbon and was constructed around the long-term changes observed in the Rothamsted classical experiments (150 years' data), and also using experimental and empirical relationships for the effects of soil temperature, moisture and clay on the decay of fresh organic materials. Some of the latter relationships were based on work in the tropics (at IITA, Nigeria) but there was no direct input from semi-arid conditions. If the model can handle semi-arid conditions acceptably, then the underlying concepts would be validated and it could be used for predictive purposes with confidence.

This model is dedicated to soil processes. Principles such as the number of C pools and descriptions of rate processes, are used in other models intended for an agronomic context. Validation of the Rothamsted approach thus underpins many other models and is of wider help in understanding sustainability of cropping. The work was centered on Trial 1, where the treatments have been maintained for 8 years. Predictive modelling of the SOM experiment was also done, but the present timespan of that experiment was judged to be not yet long enough for a real test of the model. However, soil analytical information of the initial uncultivated soil serve to substitute for the missing initial soil data in Trial 1.

Methods

The model has five pools of organic C, four active ones - decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM) and one inert pool, inert organic matter (IOM). The pattern of decay of input C is illustrated in Figure 1. Incoming organic residues are divided between DPM and RPM, depending on the type of plant material. The sizes of the pools are recalculated each month, and appropriate transfers made between the C pools. The model can also include the incorportaion of manure. The manure used in this set of experiments was from the same source was used throughout the experiment (except for a short initial period up to October 1989). It was analysed for C, N, P and K from 1992 to 1997. C content was fairly consistent at around 30%, because the manure was collected with little contamination from soil and this figure was used for the whole experimental period. Meteorological date required were rainfall and mean air temperature, available for all sites, and pan evaporation, which was available at four sites and estimated for the others by interpolation and historic data from the Kenya Meteorological Office climatological statistics.

The model was optimised on the M0 (no manure) treatment for each site. The sites were assumed to be at an equilibrium state under bush for 10^4 years until the start of cultivation (1988/9 at most sites), with an unknown C input to the soil. Then the actual/estimated C inputs for M0 were used. Fitting was done first with Machanga, because there were measurements of (i) the radiocarbon age, to help set the IOM (inert) component and (ii) standing biomass under bush, available from the vegetation survey. The C input under equilibrium and IOM pool were adjusted iteratively until a satisfactory fit was obtained for the M0 data. Then the actual C inputs for the other treatments were used, with the same initial (equilibrium) state. Thus, these other treatments are independent tests of the model.

Results

The modelled patterns of SOM change reflected the pattern of fertility change that might be expected (Figure 2). The model output suggested that the effects of manuring is quite long-lived, since manure applied from 1989 to 1992 created residues that increased the SOM in 2002, 10 years later. All the fitted curves and actual data points are shown for Machanga site (Figure 3). Perhaps because this site was the best characterised one, results were generally good here. Fits for M0 and F treatments were satisfactory, as would be expected since the model was optimised on M0, and there were only small additional inputs of plant C with fertilizer. At Machanga, and all other sites, the data for treatment M2 was simulated well by the model (Figure 3). The pattern of change under treatment R2, where manure was applied for four or five years only, was also well represented. However, at the higher manure rate, 10 t ha^{-1} per year, the model did not perform so well, and consistently overestimated the soil C (Figure 3) in the period 1993 to 1997. Up to 1993, the disagreement was not marked at Machanga, and for treatment R1, 10 t ha^{-1} manure for four or five years only, model predictions fitted acceptably to the actual data during the period of decline from 1993 to 1997.

For the other sites, similar patterns were observed, although there were some particular difficulties at Kamwaa and Kaanyaga. At Kamwaa, optimisation on M0 would lead to large overestimates of C at all other treatments, but optimisation on the fertilizer treatment gave underestimantes for M0 and the ususal pattern of fit for the other treatments. At Kaanyaga, for treatments F and R1, as well as M1, SOM-C was overestimated.

For all the sites, the results were pooled together for a general picture. There were significant differences between soils in the natural soil C. A good fit was obtained if the data were expressed as changes on the modelled equilibrium situation, ie. 1988 = 100% for all sites, instead of averaging the individual results. When this was done, the results again suggested that the low manure rates were handled satisfactorially, but the M1 treatment was not well represented by the model (Figure 4). Deviations from the modelled data were least for treatment M2.

Discussion and conclusions

Continuous manuring at 5 t ha^{-1} (M2) appeared to increased soil C at all sites except Kirimbu by 1993 (Appendix 4), but the increase was significant at only four of the original nine sites, perhaps in part because of soil variability and the need to look for a small difference in a large background. In drawing conclusions, it was necessary to bear in mind the short run of data (four years only), experimental error and lack of initial data.

The model consistently over-predicted soil C at the high manure rate. The model is linear with respect to C inputs, ie. the same % of input C is turned into DPM and RPM, no matter how much C is added. Similarly for the C which is decomposed each month, the split between CO_2, BIO and HUM is the same, no matter whether a lot or a little C is added. This is at odds with the observation that in 1993, the high manure rate did not much increase SOM, compared to the low rate. It suggests that the capacity of semi-arid soils to stabilise humified C is limited and at over about 5 t ha^{-1} manure, the capacity was exceeded. Perhaps the most important potential improvement to the model would be a non-linear relationship between input C and stabilised C.

Nevertheless, and based on experience of fitting other datasets, it was concluded that the ROTHC-26.3 model gave a generally acceptable fit to the observed C dynamics except for treatment M1. But for semi-arid conditions, the model should not be used at C inputs of over 5 t ha^{-1}.

It had been hoped that using the model would assist in describing and interpreting differences between the soils but no clear systematic differences between soils could be found. It was noted though that if the fitted IOM pool was related to the fitted total C as at 2/96 (the last sampling of all sites) the highest proportions of total C as IOM were at Gategi and Machanga. The former soil has the highest clay content. At the latter site, fertility was very low and the SOM probably provided few plant nutrients, as indicated by the poor yields without manure.

Reference

K Coleman and DS Jenkinson 1996. ROTHC-26.3 A model for the turnover of carbon in soil. Model description and users guide. ISBN 0 951 4456 6 9. IACR Rothamsted, Harpenden, Herts, AL5 2JQ, U.K.

Figure 1 - Structure of the Rothamsted Carbon Model

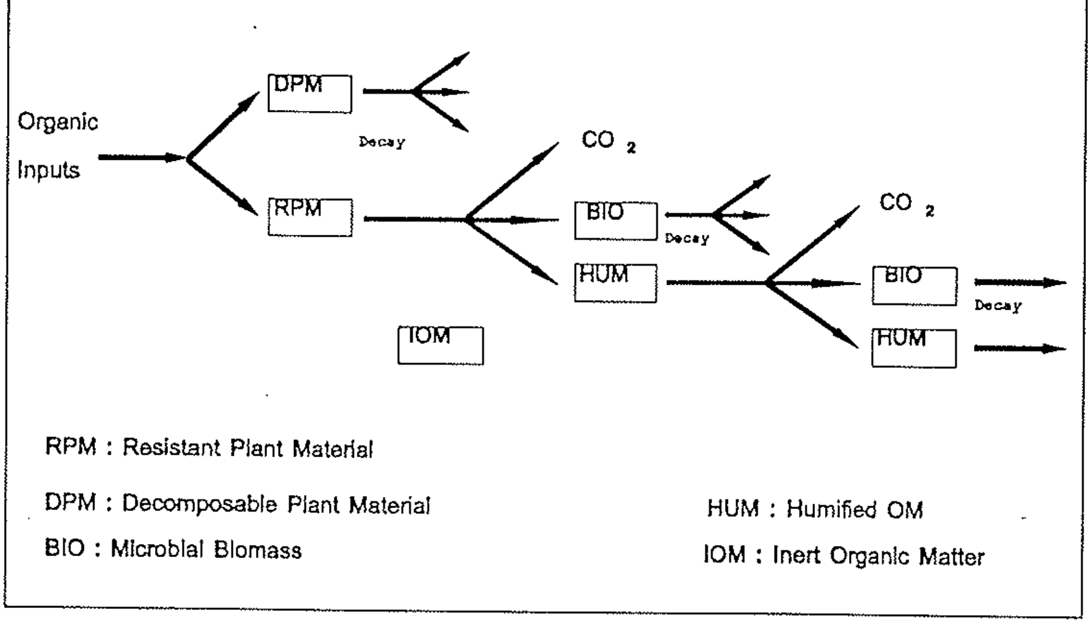


Figure 2. Modelled changes in soil organic C under the six fertility treatments at Machanga Trial 1.

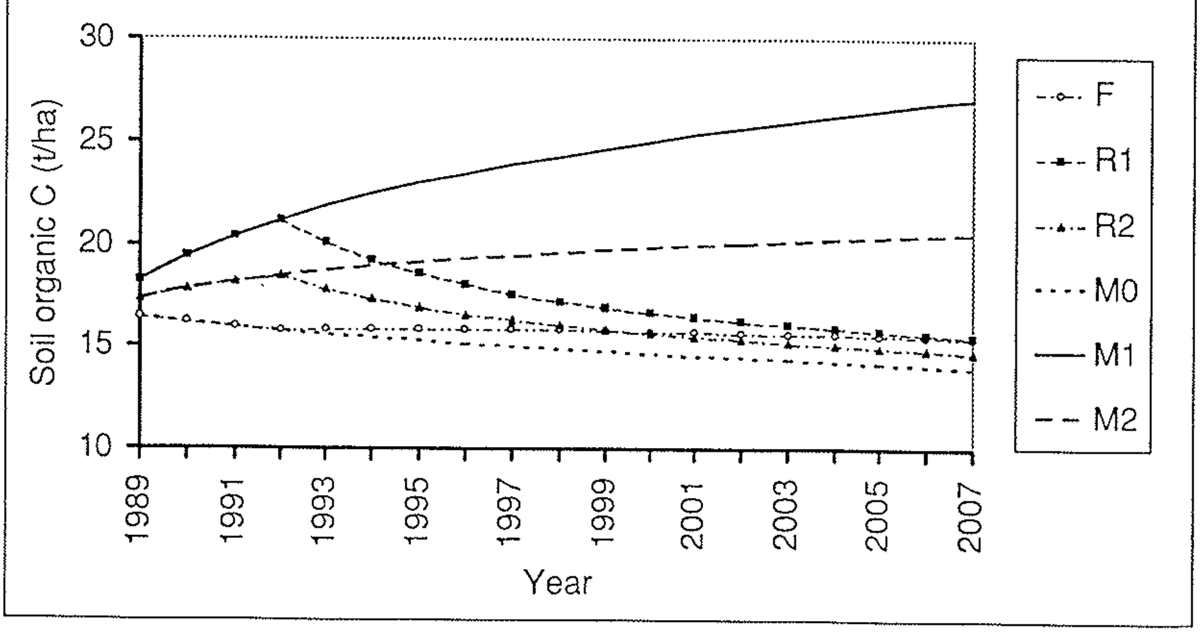


Figure 3. Actual and modelled soil organic carbon at Machanga Trial 1 site from 1989 to 1997

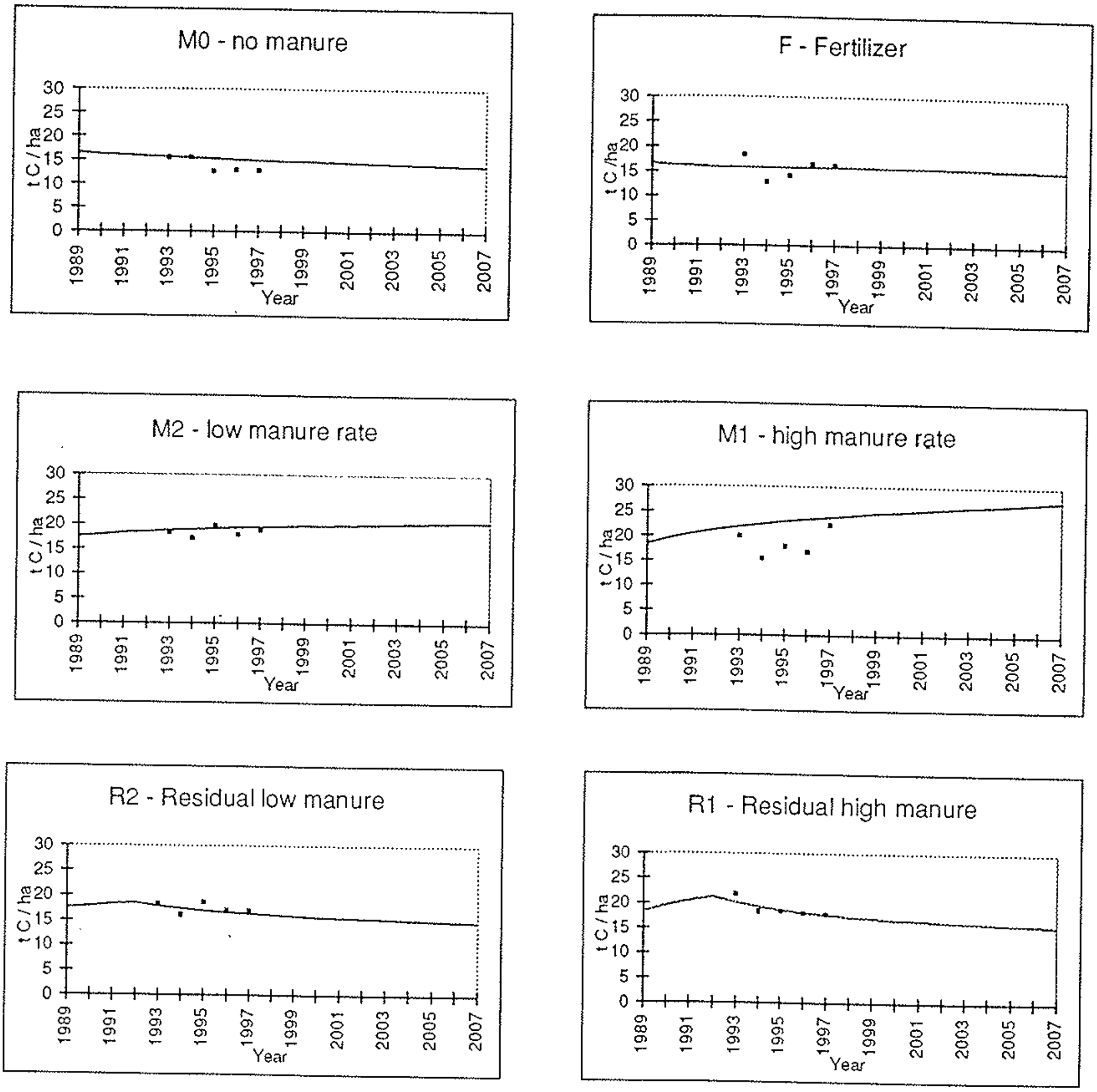
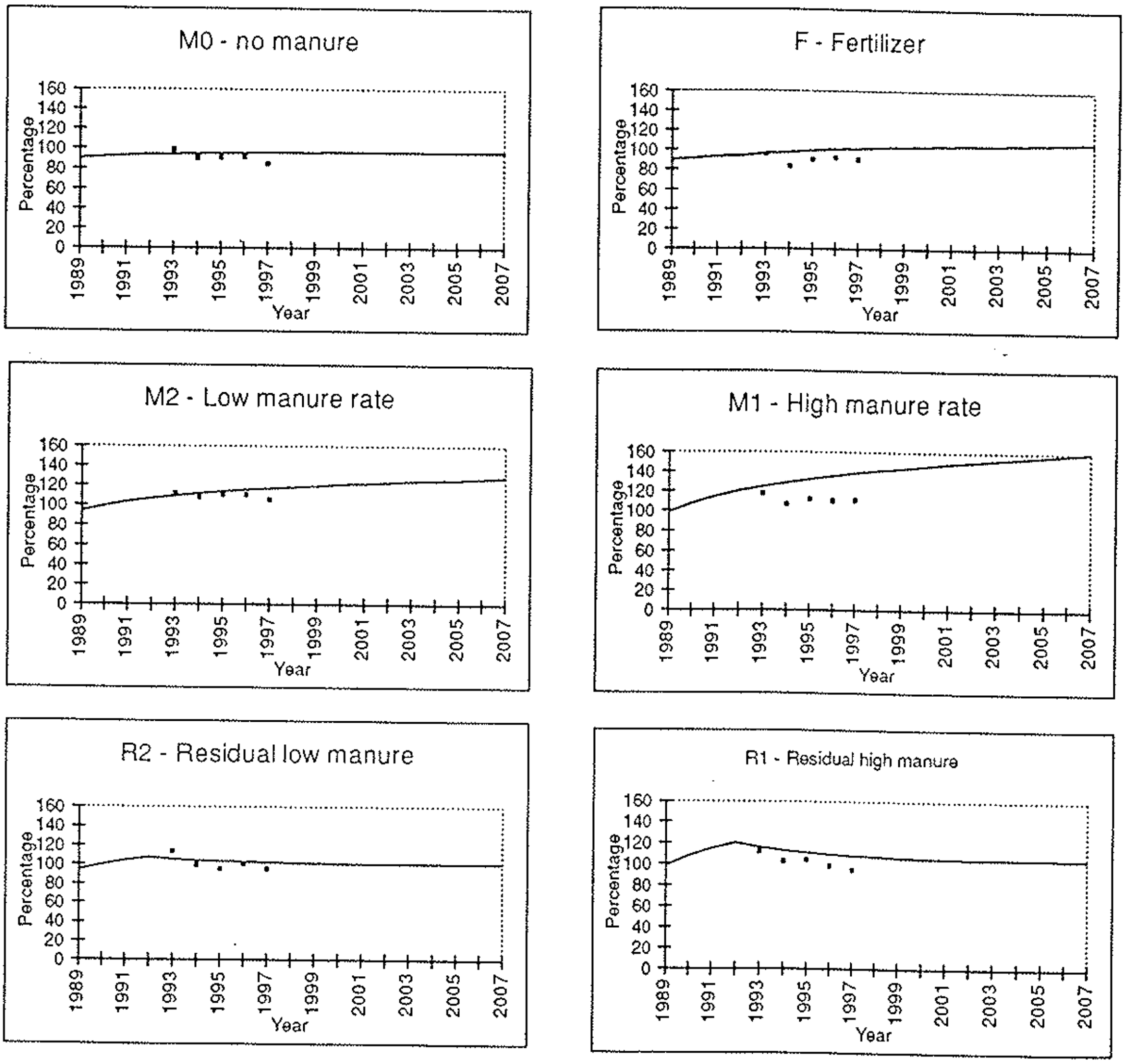


Figure 4. Changes in soil organic C in relation to 1988 values (1988 = 100%), averaged over all seven sites of Trial 1.



SOIL NITRATE DYNAMICS UNDER GRASS, SORGHUM AND BARE FALLOW IN THE FIELD EXPERIMENTS AT MACHANGA, MUTUOBARE AND KAJIAMPAU

Introduction

A major function of soil organic matter is its role as the reservoir of nitrogen (N) in the soil. Microbial decomposition of SOM releases ammonium-N, which is quickly oxidised to nitrate-N. Nitrate may be taken up by plants or lost by leaching or denitrification. The rates of all these processes vary with soil moisture content. In the November 1994 rainy season, a set of studies was made on soil nitrate at three sites in order to assess the availability of SOM-N in these soils. The sites were selected on the basis of contrasts in soil chemistry. Soil P was low at Machanga, high at Mutuobare and adequate at Kajiampau. Soil total N was lowest at Kajiampau and highest at Mutuobare (Table 1). The work was done in both Trial 1 and SOM Experiments (see Appendix 1) and in the latter experiment, values of P were similar to those in Trial 1 and N was a little higher.

In the SOM Experiment at Machanga, ammonium-N was measured three times and did not vary between sampling time and treatment (bare fallow, grass or sorghum). It was considered satisfactory to assess the changes in available soil N by measuring only the soil nitrate. Nitrate was measured at intervals of 2 to 5 days in Machanga SOM experiment and on selected occasions at the other places.

Table 1. *Selected characteristics of the sites and unmanured soils of Trial 1, as sampled in September 1994. nb: There were only small differences between the SOM and unmanured Trial 1 plots at Machanga and Mutuobare.*

	Machang'a	Mutuobare	Kajiampau
Rainfall (mm):			
Mean Annual	740	809	1040
Oct. to Jan. season	423	497	683
Oct. 1994 to Jan. 1995	439	616	862
pH (water)	6.55	6.84	7.10
pH ($CaCl_2$)	5.75	6.18	6.39
Total N [Kjeldahl] (%)	0.066	0.092	0.059
Olsen-P (mg/kg)	0.98	26.3	10.2
Texture	Sandy clay loam	Sandy clay loam	Sandy loam

Results

SOM Experiment

At Machanga, nitrate concentrations were highest soon after the start of rain (Figure 1). Under bare fallow the increase in nitrate from October 8 to 18 was significant at the 5% level, clearly demonstrating the existence of a flush of SOM decomposition (Birch, 1960) in the field situation. Within another week, most nitrate had been lost. Under bare fallow and sorghum, nitrate concentration increased during dry weather and losses occurred when soil water content exceeded 10%. Modelling of soil water movement indicated that there was no leaching below the rooting zone, so denitrification may be the main route for loss of soil N.

Nitrate concentration was lower under sorghum due to plant uptake (Figure 2). Under grass, nitrate remained very low throughout the season because the dense, permanent rooting system could take up mineralized N quickly. In the P fertilized treatments, nitrate concentration was lower throughout the season and sorghum N uptake increased.

Estimates of net mineralization under bare fallow were made from the increases in nitrate during the three main dry periods (Table 2). It was found that a total of approximately 57.6 kg N ha^{-1} was made available during the season, exceeding the total above-ground N uptake of 51.9 kg N ha^{-1} in the P fertilized treatment.

At P-rich Mutuobare, vigorous sorghum growth kept soil nitrate concentration low, even though N mineralization was faster than at Machanga, as indicated by higher initial nitrate and a faster increase late in the season in bare fallow.

Table 2. *Accumulation of nitrate-N in the 0-15 cm horizon of unfertilized Machang'a bare fallow, at the end of each period of net mineralization.*

	Increase in nitrate-N concentration (mg N kg^{-1})	Amount of mineralized nitrate-N in topsoil on the last day (kg N ha^{-1})
Mineralization period		
Before Day 18	14.08	26.2
Day 23 to Day 33	3.41	6.3
Day 37 to Day 67	5.25	9.8
Day 70 to Day 117	8.22	15.3
Total	-	57.6

Trial 1

Soil nitrate was measured in all the manured treatments (Part 1: Introductory Paper 2) and control. Because of the infrequent sampling, interesting details of the nitrate dynamics such as the early season flush were missed. However, the general temporal pattern was the same as at Machanga SOM. Topsoil nitrate concentrations were highest at the start of the season, and within about 15 days, most nitrate had been lost and differences between soils and treatments were much smaller. At the beginning of the season the response of nitrate to manure normally followed that pattern that might be expected ie. higher at the high manure rate and higher in soils under continuous manuring compared to soils where manure was last applied in October 1992. At the end of the season nitrate was significantly higher in soils with 10 t ha^{-1} continuous manure than the other treatments at Mutuobare and Kajiampau. During days 49 to 80 at Machanga, nitrate was significantly higher in the *unmanured control* compared to other treatments (Figure 3).

Nitrate N correlated with N taken up by crops on many occasions at Kajiampau, where N was the main limiting nutrient, but not at Mutuobare or Machanga (Table 3). The wide variations of measured nitrate between sites and sampling dates make it unsuitable as a practical indicator of N requirements for crops. Total soil N was correlated with N taken up by the sorghum at all sites and the degree of correlation increased in the order Machanga < Mutuobare < Kajiampau.

Conclusions

At Kajiampau, the crops responded mainly to N in the manure, indicated by close correlations of soil N with crop N uptake, whereas at Machang'a, the crops responded mainly to P in the manure.

For all soil types, nitrate contents were highest at the start of the season and increased again towards the end of the season. Large losses of nitrate were found early in the season under all treatments except grass. Thus the natural pattern of N availability was poorly matched to crop demand, which is most during the middle part of the season. Application of N fertilizer early in the season is not recommended as it would be lost with the initial native soil nitrate. At present, mineral fertiliser N should not be recommended to farmers for these areas, but research should be carried out into top dressing, since N was clearly limiting at some places such as Kajiampau.

The continuous high manure rate resulted in additional surplus nitrate at the end of the season, which would be lost at the start of the following season. A maximum manure rate of 5 t ha^{-1} is indicated to reduce losses of N. At the lower application rate, manure had significant effects in the fifth season after application (see agronomy results), so the frequency of application could be varied within that maximum application rate. This gives opportunities for labour saving management in scheduling of applications.

The use of P fertilizer at the P-deficient site reduced soil nitrate and increased sorghum N uptake. At the P-rich sites, vigorous sorghum growth kept soil nitrate concentration low, even though much nitrate was produced and lost in bare fallow. Therefore, adequate soil P is essential to manage efficiently the natural N resources of soil.

Although N is supplied from soil to plant roots in the form of nitrate, the amounts of nitrate at any time were not well related to yield and N uptake. Total N is the better indicator of the fertility of the soil with regard to N, and could be calibrated for soils of the area.

Table 3. *Correlation coefficients between (i) total N uptakes (grain plus residues) by sorghum or cowpeas and (ii) soil nitrate or soil total N for three sites of Trial 1.*

Sorghum N uptake

	Planned Sampling Day†	Machanga	Mutuobare	Kajiampau
Total-N	0	0.628*	0.657**	0.760***
Nitrate-N	10	0.166	0.423	0.444
	25	0.326	0.656**	0.645**
	50	-0.337	0.406	0.397
	75	-0.503	0.640*	0.678*
	100	0.102	0.450	0.310
	120	0.077	0.442	0.328

Cowpea N uptake

	Planned Sampling Day†	Machanga	Mutuobare	Kajiampau
Total-N	0	0.171	-0.049	0.524*
Nitrate-N	10	0.608*	0.345	0.578*
	25	0.609*	0.253	0.603*
	50	-0.102	0.147	0.641**
	75	-0.035	0.359	0.762**
	100	0.355	0.374	0.544*
	120	0.163	0.137	0.764**

†The actual dates varied between sites and are given in the text.
*, **, and *** denote correlations significant at the 5, 1 and 0.1% levels respectively.

References

Birch, H.F. (1960). Soil drying and soil fertility. *Tropical Agriculture, Trinidad* 71: 3-10.

Warren, G.P., Atwal, S.S. and Irungu, J.W. 1997. Soil nitrate variations under grass, sorghum and bare fallow in semi-arid Kenya. Experimental Agriculture 33: 321-333.

Figure 1. Soil nitrate in Machanga SOM site, bare fallow soil, in relation to soil water content, November 1994 season.

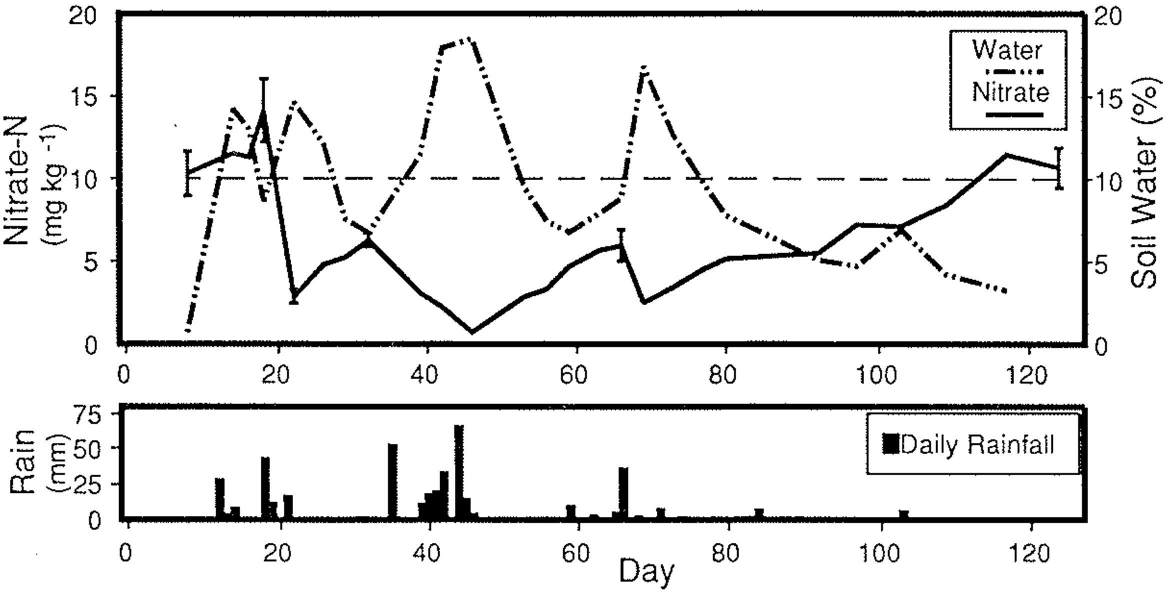


Figure 2. Soil nitrate at Machanga SOM site, November 1994 season.

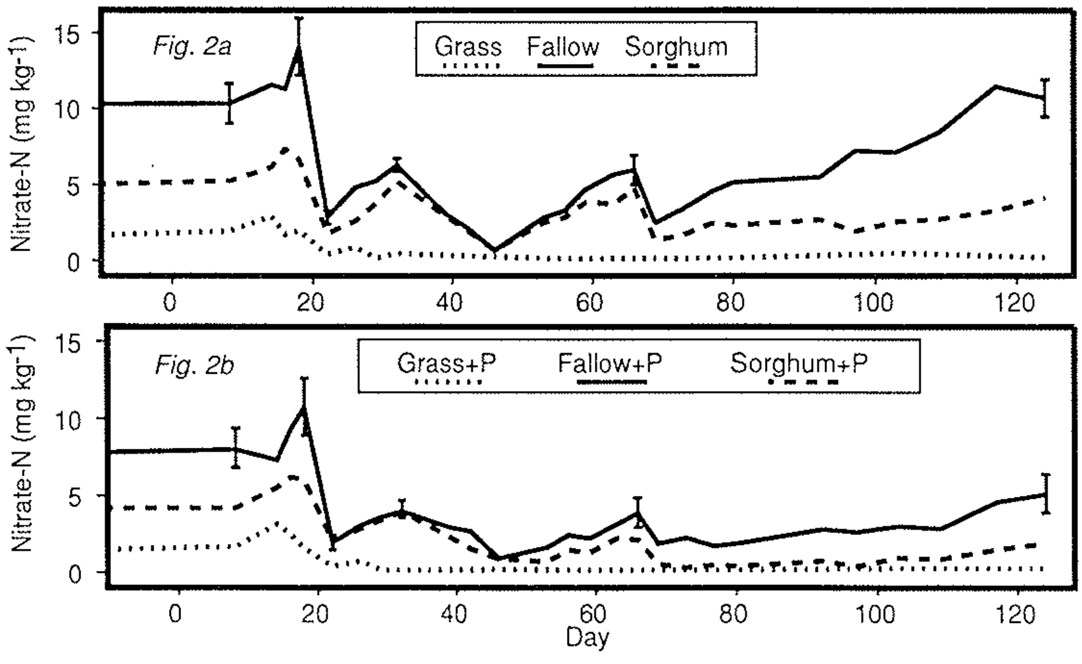
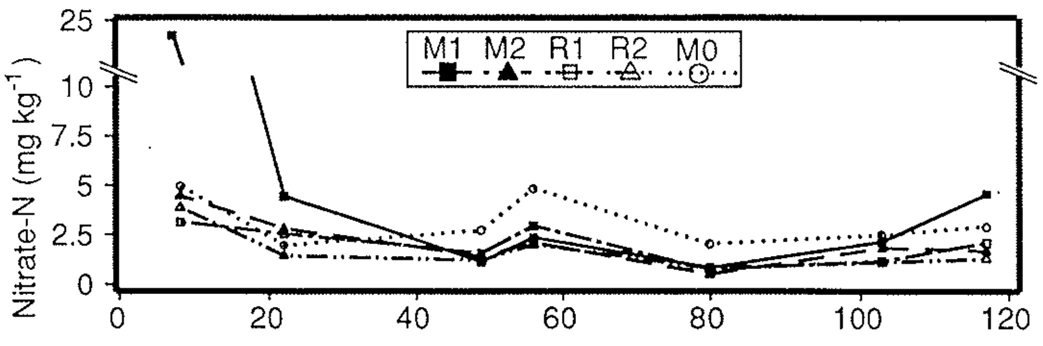


Figure 3. Soil nitrate at Machanga Trial 1, November 1994 season.



DYNAMICS OF EXTRACTABLE P AND FIELD BALANCES OF P IN TRIAL 1

Introduction

The sustainability of an agricultural system should be assessed by measurable indicators, such as trends in crop yields, trends in soil composition and nutrient balances of the system. Nutrient balances are suggested as a suitable indicator of sustainability regarding soil fertility (Smaling et al. 1996), but estimates of the inputs and outputs of N, P, K etc. for farmers' fields are subject to many errors. Observation of trends in crop yields and soil chemistry requires a long time-scale for the work. Because it was established in 1988/9 and continued with the same crops until 1997 (Appendis 1), Trial 1 provides an opportunity to try out all three approaches to the assessment of sustainability mentioned above. Soil analysis was not undertaken in the first phase of the experiment (before 1993), so the picture is incomplete, but trends in soil P status were investigated in the 1993-7 period. The objectives of the work described here were (i) to assess the trends in soil available P and (ii) to relate the the trends to the P balance of the fields.

Methods

During the second (1993-97) phase of Trial 1, the field treatments were: (code M0) no manure; (M1) manure at 10 t ha^{-1} annually; (M2) manure at 5 t ha^{-1}; (R1) residual effects of 10 t ha^{-1} of manure applied in the first phase (1989-93); (R2) residual effects of 5 t ha^{-1} of manure applied in the first phase, and (F) N and P fertilizers applied at rates close the N and P supplied in treatment M2. The annual rates of N and P applied in treatments M2 and F were approximately 102 kg N ha^{-1} and 24 kg P ha^{-1}. The fields were cropped to sorghum/cowpea intercrop and millet/green gram intercrop as described above (Appendix 1). Each season from the 4/93 season to the 11/96 season, samples were taken of the crops at harvest. Each crop (cereal and legume) was sampled separately and divided into grains and residues (all above-ground crop residues were combined). Samples were taken for all plots at all sites. Total N and P in the samples were measured by the KARI National Agricultural Research Laboratory. Samples of the manure used were taken at each site, and total C, N, P and K measured at Reading.

Soil was sampled from all plots of the above treatments at all seven sites in February each year from 1993 to 1997, except that financial constraints caused the Kamwaa and Kaanyaga sites to be closed a year early after the 1996 sampling. All samples were air-dried, ground to pass a 2mm sieve, and analysed at Reading. Extractable P was measured by the Olsen method, 0.5M $NaHCO_3$ at pH 8.5. The method is sensitive to the extraction temperature and particular attention was paid to the extraction conditions. All samples were extracted for 30 minutes at 20°C in a controlled temperature room.

Results and discussion

Effects of manure on trends in Olsen-P.

In the first phase (1989-1993), manure significantly increased Olsen P relative to the M0 treatment at all sites (Appendix 4). Over the period 1993 to 1997, these basic differences between the three continuous manure treatments in Olsen-P were maintained ($M0<M2<M1$). There was considerable variability in the data between plots and from year-to-year. Nevertheless, linear relationships with time were fitted by simple regression, to quantify the trends. An example of the data and trends is illustrated (Figure 1) and the parameters of all the fitted lines are given (Table 1). The mean trend for each treatment over all sites was calculated from the parameters of the individual fitted lines.

For the continuous manure treatments (M0, M2, M1) the coefficients of time in the regression trends were not significantly different from zero, except for M1 at Gacheraka. Although the slopes were not significantly different from zero, the following small trends were noted: (i) downwards in M0, (ii) almost level for 5 t ha^{-1} manure and (iii) upwards for 10 t ha^{-1} manure. These comparative trends were seen distinctly for the all-sites means (Figure 2). Unfortunately, soil samples were not taken at the start of the field experiment in 1988/9, so the soil P status before the start of manure application is unknown. To make an estimate, the trend line for M0 was projected back to 1989 (Figure 2), on the assumption that the depletion of available P in M0 continued at the same rate over the whole cropping period. Using this projected 1989 Olsen-P, the trends in Olsen-P from 1989 to 1993 were positive in both manured treatments (Figure 2). The 1993-7 trends were much closer to zero. Thus the Olsen-P in each continuous manure treatment was tending towards a new dynamic equilibrium in 1993-7, with small net changes after the initial divergence of the treatments.

After manure application ceased in 1993 (treatments R1 and R2), there were significant declines in Olsen P at many sites (Table 1). Olsen P in the former 5 t ha^{-1} manure treatment was almost down to the Olsen P in M0 by 1997. In the residual 10 t ha^{-1} manure treatment, Olsen P was about the same as in the continuous 5 t ha^{-1} treatment. This suggested that the higher manure application rate, the longer lasting the P residual effect.

In treatment F, fertilizer application started in 1993 and the mean annual amount of total P applied was 24 kg ha^{-1}. The trend in Olsen-P from 1993-97 was approximately parallel to the projected trend in Olsen-P from 1989-1993 in treatment M1 (Figure 2), so both F and M1 treatments increased extractable P at the same rate over time. This suggests that treatments F and M1 supplied the same amount of inorganic phosphate-P. Phosphate-P is released from the manure by mineralization. It would be expected that the mineralized phosphate-P would be split between Olsen-P and "fixed" inorganic P in the same way as phosphate-P supplied by mineral P fertilizer. However, treatment M1 provided approximately twice the amount of total P (48 kg ha^{-1}). Therefore, this result suggested that the other half of the P supplied in manure remained in stabilised organic P fractions without passing through a mineralised inorganic phosphate fraction. This reserve of organic P is a potentially important medium-term (over a period of a few years) reserve of soil P that would have a positive influence on the sustainability of soil fertility.

Relationships between field balances for P and Olsen-P.

Balances for P in the fields (P inputs minus P offtakes) were calculated for the six harvests from 1993 to 1996 inclusive, using the analyses of the crops and manures. There was considerable season-to-season variability of yields and nutrient offtakes, so interpretation was based on the cumulative balances. At all sites, the manured treatments resulted in clear positive balances for P (Figure 3). Potential differences between sites may exist, but could not be identified in these results.

Surplus manure P, not required by the crops would be added to both labile (extractable) and non-labile pools of soil P. The hypothesis was proposed that the trend in Olsen-P was proportional to the net P balance. Thus, for continuous manuring, the larger the unused manure-P, the larger the annual increase in Olsen-P. A graph of P input against Olsen-P trend should then give a positive slope. To test this, the mean annual P balance (from data presented in Figure 3) and the mean anual change in Olsen-P (from data presented in Table 1) were calculated for each treatment. The relationships were plotted for each site (eg. Figure 4). The expected relationship was found for most sites, although not all were as good as at Machanga, eg. at Kamwaa M0 (no manure), an apparant increase in Olsen-P conflicted with a negative P balance. However, the difference between M1 and M2 could be used to estimate the response of Olsen-P trend to P balance. Some differences between the sites were observed for the increase in Olsen-P, in response to unused manure-P (Table 2: column 1).

The positive relationship between P balance and trend in Olsen P as illustrated in Figure 4, could be used to calculate estimates of the fate of the unused manure P. It was assumed that all manure P was retained in the sampling horizon (0-20 cm) and the mean annual change in Olsen-P was converted from mg P kg^{-1} soil to kg P ha^{-1}. To do the conversion, the weight of 0-20 cm soil per ha was estimated from the soil bulk density. For Machanga, 3.7% of the unused manure P was converted to Olsen-P (Table 2: columns 2 and 3). The range of the conversion was from 1.1 to 20.5%, suggesting that 79.5 to 98.9% of the unused manure P stayed in the soil as "fixed" inorganic and unmineralized organic forms. It was also observed that the higher the Olsen P in unmanured soil, the lower the proportion of immobilized manure P (Figure 5). Thus the amount of Olsen P in an unfertilized soil may also indicate its potential for immobilization/fixation.

For the soils where manure application was ceased, crop growth and P offtake were limited by constraints other than available P. In general, yields and P offtakes were little more in R1 compared to R2, while the concentrations of Olsen-P were a lot more in M1 and R1 compared to M2 and R2 in 1993, at the start of the fertility run-down (Appendix 4). It was easier to consider the R1 and R2 results separately from the continuous manure results, by thinking in a "depletion" sense by working left and down from the origin (x=0, y=0) in Figure 4. Thus, in a comparison of R1 (former high manure) and R2 (former low manure), the extra depletion of soil P (a more negative value for P balance) was associated with a worse (more negative) Olsen-P decline. However, the mean extra offtake from the R1 treatment was less than the mean extra depletion of Olsen P (Table 3). This suggests that in the R1 treatment, the depletion of labile-P was able to supply all or most of the extra crop P requirement. The rest of the Olsen-P was converted from inorganic labile form (Olsen-P) to non-labile forms, which would probably include inorganically "fixed" P.

Conclusions

Qualitative relationships between P balance and trends in Olsen-P were developed for most sites. However, high levels of variation made it impossible to show significant differences between sites. Where there was a positive balance of P in the field, the extractable P showed an upward trend. It was clear that this upward trend was much faster in the first phase of continuous manuring (1989-1993) than in the second phase (1993-1997). These results agree with the concept that there is a dynamic equilibrium between labile and unavailable forms of soil P. As the amount of labile P (represented by Olsen-P) increased over time, there was a higher conversion to non-labile P.

Some of the unused manure P was converted to the labile form (Olsen-P) and some of the rest would be converted to "fixed" inorganic P. This was also suggested by the results for P balances in (i) the residual high manure treatment (R1), where Olsen P declined more rapidly than was accounted for by plant uptake, and (ii) fertilizer-P treatment (F) where surplus P would start as an inorganic form. However, none of the soils was either strongly acid or calcareous, and sorption of inorganic P was never high (Appendix 4), so severe "fixation" of P is not an issue for these soils. Thus the results suggest that much unused P was converted to stabilised organic forms, in agreement with the comparisons of the trends in Olsen-P for manure and fertilizer treatments. The newly formed soil organic P could persist over several years and positively influence sustainability of soil fertility.

Reference

Smaling, E.M.A., Fresco, L.O. and de Jager, A. 1996. Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio 25, 492-496.

Table 1. *Parameters of the regression equation P=a+bt describing trends in Olsen-P (P) with time (t), from 1993 to 1997. (1993 = Year 1).*

M0: No manure

	a	*b*
Gatcgi	1.533	- 0.077
Machanga	1.006	- 0.007
Mutuobarc	35.873	- 1.453
Kamwaa	3.591	+ 0.101
Kajiampau	10.380	- 0.981
Gacheraka	1.685	+ 0.016
Kaanyaga	5.766	- 0.086
Mean	8.548	- 0.355

F: Fertilizer (24 kg P ha^{-1} per year)

	a	*b*
Gatcgi	1.575	+ 0.704 **
Machanga	1.581	+ 0.737 **
Mutuobarc	23.265	+ 3.168 *
Kamwaa	3.008	+ 1.580 **
Kajiampau	10.521	+ 1.004
Gacheraka	2.983	+ 0.565 *
Kaanyaga	6.400	+ 0.415
Mean	7.048	+ 1.167

M2: 5 t ha^{-1} manure every year

	a	*b*
Gatcgi	5.365	- 0.193
Machanga	1.853	+ 0.214
Mutuobarc	37.777	+ 0.218
Kamwaa	12.546	- 1.217
Kajiampau	15.613	- 0.120
Gacheraka	3.007	+ 0.131
Kaanyaga	5.258	+ 0.503
Mean	11.631	- 0.066

M1: 10 t ha^{-1} manure every year

	a	*b*
Gatcgi	7.161	+ 0.359
Machanga	4.267	+ 0.503
Mutuobarc	57.198	+ 1.639
Kamwaa	16.001	- 1.134
Kajiampau	24.767	- 1.088
Gacheraka	4.250	+ 0.686 *
Kaanyaga	8.354	+ 0.284
Mean	17.428	+ 0.179

R2: 5 t ha^{-1} manure, 1989-92 only

	a	*b*
Gatcgi	7.362	- 1.528 *
Machanga	1.871	- 0.143
Mutuobarc	31.214	- 1.005
Kamwaa	9.969	- 0.476
Kajiampau	16.564	- 1.429
Gacheraka	2.395	- 0.090
Kaanyaga	6.827	- 0.208
Mean	10.779	- 0.697

R1: 10 t ha^{-1} manure, 1989-92 only

	a	*b*
Gatcgi	6.773	- 1.124 *
Machanga	3.567	- 0.617 *
Mutuobarc	52.174	- 2.931
Kamwaa	12.794	- 1.786
Kajiampau	24.557	- 2.388 *
Gacheraka	3.844	- 0.458 **
Kaanyaga	8.849	- 0.052
Mean	16.080	- 1.337

* and ** denote that the regression coefficient *b* was significant at the 5% and 1% levels respectively.

Table 2. *Relationships (regression coefficient) between the mean annual increase in Olsen-P and the mean annual P balance for continuously manured treatments, and estimates of the partitioning of unused of manure P into extractable (Olsen-P) and non-extractable (immobilized) fractions.*

	Coefficient: Increase in Olsen P (mg kg^{-1}) / P input (kg ha^{-1})	**Partitioning of 100 g unused manure P between labile and non-labile P**	
		Olsen P (g ha^{-1})	Immobilized P (g ha^{-1})
Gategi	0.0089	2.6	97.4
Machanga	0.0132	3.7	96.3
Mutuobare	0.0698	20.5	79.5
Kamwaa	0.0036	1.1	98.9
Kajiampau	0.0496	12.4	87.6
Gacheraka	0.0168	5.6	94.4
Kaanyaga	0.0340	11.1	85.9

Table 3. *Depletion of labile P under fertility decline in the residual manure treatments. Comparison (R1 - R2) of the former high manure (R1) and former low manure treatments (R2), for (i) the annual rate of depletion of labile P (Olsen P) and (ii) the extra P uptake.*

	Olsen P depletion in R1 (kg ha^{-1})	**Extra P uptake in R1** (kg ha^{-1})
Gategi	1.18	1.70
Machanga	1.31	0.90
Mutuobare	5.64	0.82
Kajiampau	2.89	0.10
Gacheraka	1.22	-0.03
Kaanyaga	0.51	1.47
Six sites	2.13	1.33

Figure 1. Trends in Olsen-P from 1993 to 1997 in the M0 (no manure) treatment at each site, with fitted regression lines.

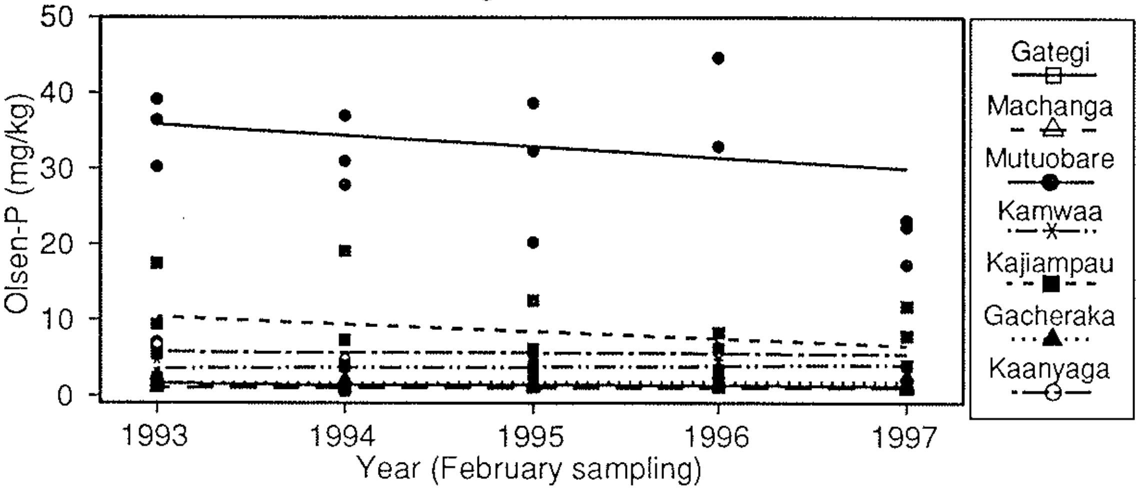


Figure 2. All-sites means for the fitted trends in Olsen-P from 1993 to 1997 with projections back to 1989.

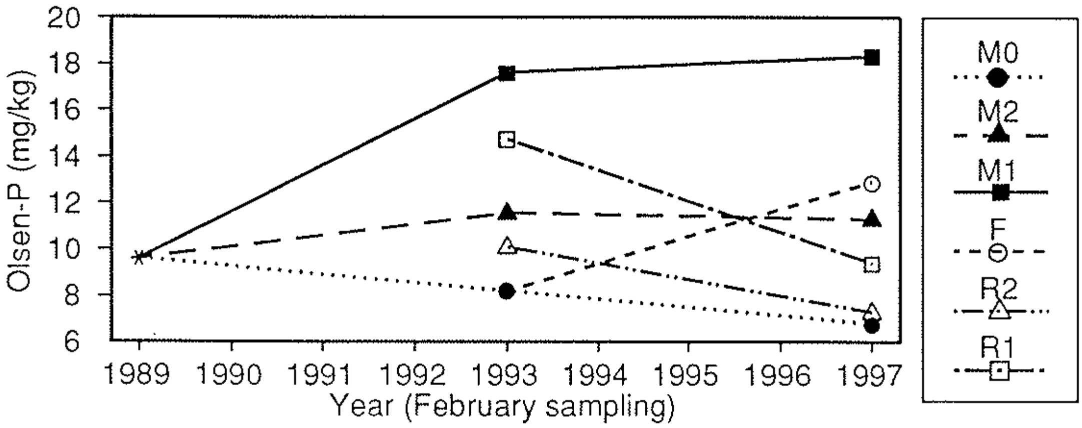


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Figure 3. Cumulative P balance over six seasons, from March 1993 to February 1996, for continuous manure treatments.

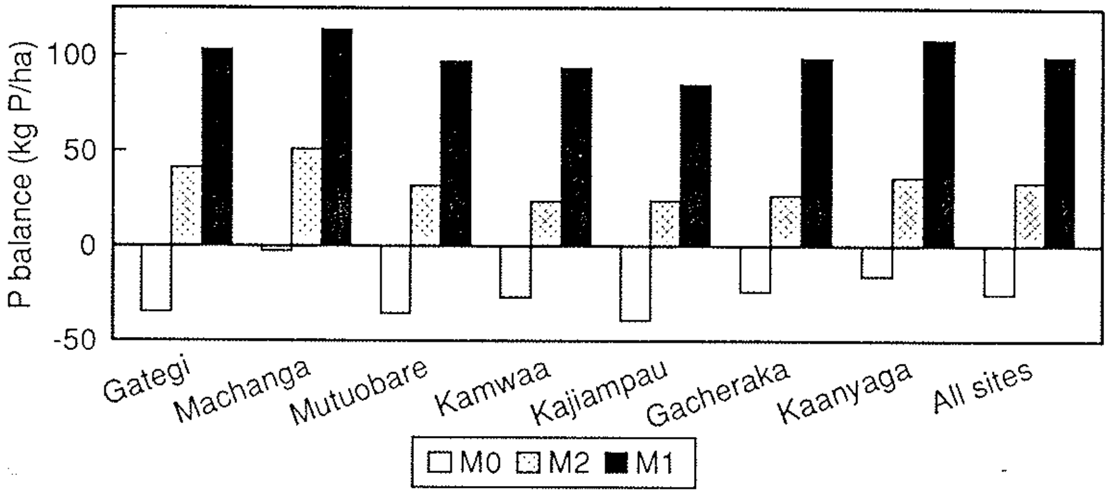


Figure 4. Mean annual rate of change in Olsen-P (mg/kg) in relation to the mean annual P balance (kg/ha) at Machanga site, for five field treatments.

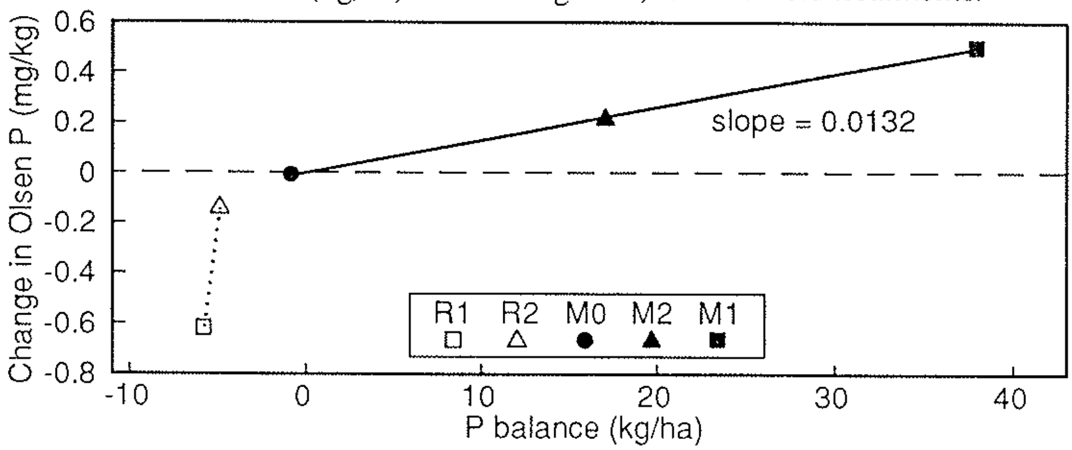
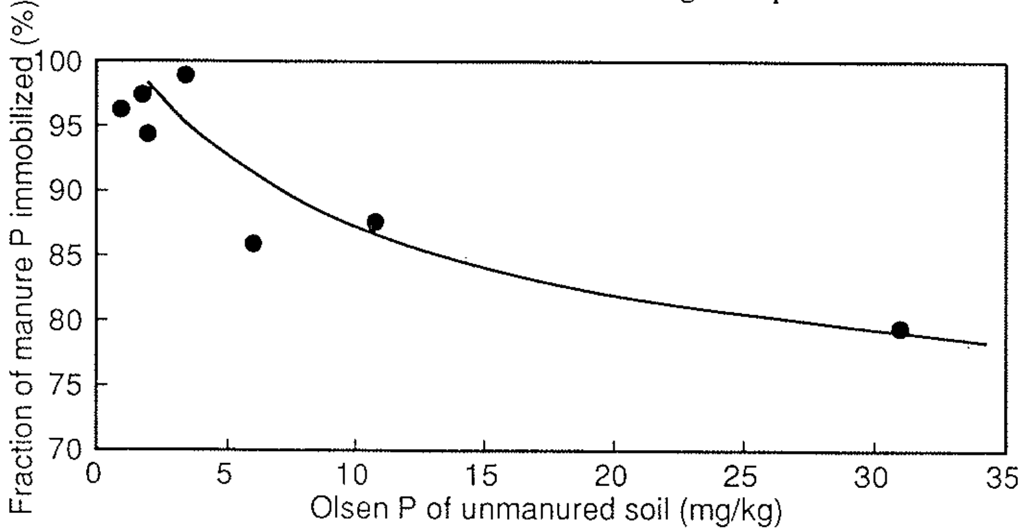


Figure 5. Relationship between immobilization of unused manure P and Olsen P in unmanured (M0) soil, with a smoothed line through the points.



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EFFECTS OF NATIVE SOIL PHOSPHORUS ON BIODIVERSITY, PRODUCTIVITY AND THE DYNAMICS OF SOIL CARBON AND NITROGEN AT MACHANG'A AND MUTUOBARE SITES.

Introduction

Soil, natural vegetation and agronomy have been investigated at, Machang'a and Mutuobare, two sites with contrasting natural soil fertility. Results of several studies have been brought together in this paper for a broad picture of soil fertility.

Sites

Machang'a and Mutuobare are experimental agriculture sites of the Kenya Agricultural Research Institute (KARI), in the Mbeere District of Kenya and near 1°S 35°E. The climate is semi-arid with about 800 mm rain per year, bimodally distributed (Table 1). The soils are Chromic Cambisols (about 1 m deep) overlying granitoid gneiss (van de Weg and Mbuvi, 1975) and the major soil clay minerals are kaolinite and illite. Many properties of the two soils (e.g. pH, mineralogy, K content) are similar (Table 1). The sites differ because Mutuobare soil is rich in available native soil P, shown by (i) the high amount (30 mg kg^{-1}) of extractable P (Olsen method; 0.5M $NaHCO_3$) and (ii) the composition of the topsoil fine sand (0.05 to 0.2 mm) which contains 35% of apatite (Plum, 1994).

Table 1. *Characteristics of the sites and soils.*

	Machang'a	Mutuobare
Altitude (m)	1050	900
Rainfall (mm): Mean Annual[a]	740	809
October to January season[a]	423	497
October 1994 to January 1995	439	616
Mean annual temperature (°C)	23	25
pH (water)	6.47	6.54
Total C [combustion] (%)	0.921	1.18
Total N [Kjeldahl] (%)	0.078	0.098
Olsen-P[b] (mg P kg^{-1})	0.87	30.0
Sand (%)	46	59
Silt (%)	30	21
Clay (%)	24	18
Bulk density (<2mm soil)	1.28	1.30

[a] Mean, 1989-1995

[b] Extracted by 0.5M $NaHCO_3$ at pH 8.5

No arable cultivation had occurred on the experimental areas in recorded times. So the sites represent stable ecosystems in which man's impact has been the traditional long-term, low-intensity uses of grazing and wood harvesting. Grazing has influenced the sites; by domestic goats and cattle in recent decades and by wild herbivores before.

Soil organic matter composition

In the topsoil, radiocarbon (^{14}C) dating (Warren and Meredith, 1997) showed that soil organic matter (SOM) was always >100% modern (Table 2), so its mean age is more recent than 1950. Radiocarbon ages can be given to the lower horizons at Machang'a and Mutuobare, which were dated at 835 and 415 years BP (before present: 1950) respectively. Thus the SOM-C of the lower horizons is rich in resistant fractions of humic matter, although it must be remembered that SOM-C is in a state of turnover. Some recently formed SOM always exists and there is a continuum of different age fractions within the overall mean age. Inputs of C to soil are from roots and surface litter, and are thus smaller in lower horizons. Therefore, the concentration of SOM-C decreased down the profile, while carbon age increased (Table 2).

Table 2. *Organic C (mg g^{-1}) and radiocarbon (^{14}C) age of organic C, expressed as % modern (relative to 1950) in each horizon.*

Horizon	*Organic C*		*Radiocarbon age*	
	Machang'a	Mutuobare	Machang'a	Mutuobare
0-20 cm	8.8	10.9	103.4	110.2
20-35 cm	6.1	6.1	90.1	94.9

The Mutuobare surface horizon had more soil organic matter carbon (SOM-C) compared to Machang'a (Table 2). This is ascribed to the visibly greater standing plant biomass at Mutuobare, giving larger C inputs at the surface. Below 20 cm, the concentration of SOM-C was the same in the two soils. Topsoil SOM-C was younger at Mutuobare than Machang'a, suggesting that the additional SOM-C formed by vigorous plant growth was added to a fast-turnover pool.

Natural biodiversity

In May 1995 the natural species composition was assessed at both sites (Kinyamario, 1997). The number of species was counted in 15 quadrats (1 x 1 m) on undisturbed bush at each site. Species diversity was markedly greater at Machanga (45 spp.) than at Mutuobare (27 spp) and 17 species were common to both sites (Table 3). The natural climax vegetation was *acacia-commiphora* bush. Trees at Machanga gave an incomplete canopy cover, and the density of vegetation appeared greater at Mutuobare, in line with its higher soil fertility. The canopy cover by woody species was assessed by measuring segments of transect lines which were covered by individual plants. At Mutuobare, high soil P favoured indigenous N fixing species, since *acacias* (N fixing) accounted for more than half of the canopy cover (52%), whereas at Machang'a, *commiphoras* (non-fixing) covered nearly twice the area of *acacias* (Table 4).

Table 3. *Biodiversity of undisturbed bush: Numbers of plant species*

	Machang'a	Mutuobare
Trees	16	6
Grasses	14	9
Other herbs	11	12
Total	45	27

Table 4. *Biodiversity of undisturbed bush: Woody species canopy cover (%).*

	Machang'a	Mutuobare
Acacias	19	52
Commiphoras	34	21
Other species	47	27

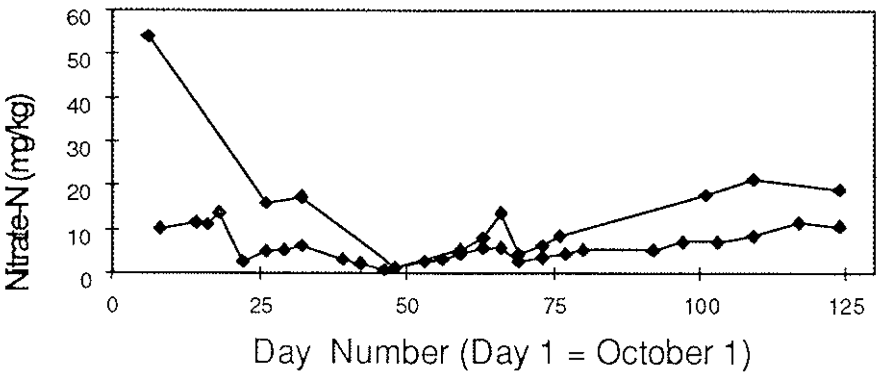
Dynamics of mineral N

In February 1994, part of each site was cleared and the following treatments set up:

Sorghum:	Cropped to sorghum and above ground dry matter removed.
Bare fallow:	Tilled by hand every month.
Grass fallow:	Bush cut to the surface without disturbing the soil; natural grass regrowth permitted and maintained by cutting 2 or 3 times per season.

The dynamics of soil N were studied by measuring extractable nitrate every few days during the rainy season from October 1994 to January 1995 (Warren et al. 1997). Changes in nitrate concentration were related to the rainfall pattern: after heavy rain, rapid losses of nitrate occurred. Although it could not be confirmed directly, the most likely loss mechanism was denitrification because (i) modelling indicated that rainfall was not enough for leaching beyond the rooting zone and (ii) no accumulation of nitrate was found in soil samples taken down to 1 m depth in selected plots. In dry weather, nitrate increased and the rate of increase was faster at Mutuobare than Machang'a, for example between days 55 and 65, and again between days 70 and 110 (Figure 1). Mutuobare soil contained up to five times more nitrate than Machang'a, although total soil N was only 25% more (Table 2). Mutuobare soil was therefore richer in readily mineralisable fractions of soil organic nitrogen.

Figure 1. Soil nitrate concentrations at Mutuobare (upper line) and Machang'a (lower line) from October 1994 to February 1995.

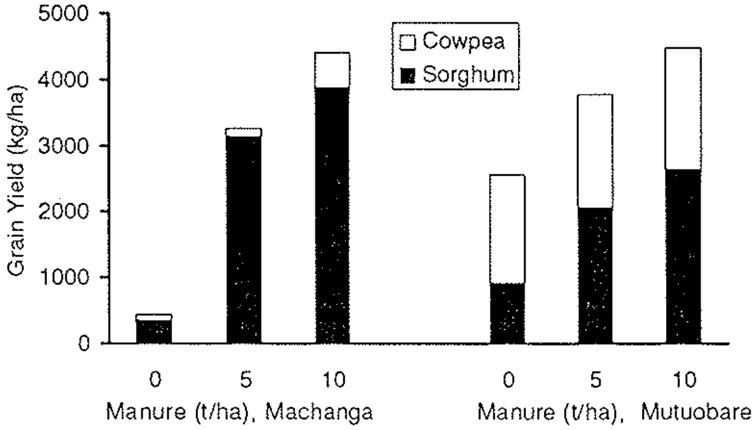


Agronomic results: response to manure by intercropped sorghum and cowpeas

The effects of manuring were assessed in a companion experiment which was adjacent to the main experimental area at Mutuobare. At Machang'a it was 500 m away but located on the same soil. From 1989, goat manure was applied 0, 5 and 10 t ha^{-1} per year and the plots cropped to sorghum/cowpea and millet/green gram in rotation. At Machang'a, there was always a response to manure, but responses at Mutuobare were usually small or non-significant (Gibberd (1995)

In the 1994-5 season, sorghum and cowpea responded to manure at both sites, but cowpea yields were always much more at Mutuobare than at Machang'a (Figure 2). With 10 t ha^{-1} manure, total yields were similar at the two sites, but the proportion of legume yield was lower at Machang'a (Figure 2). This suggests that despite the addition of P by manure, the native P at Mutuobare was more effective for cowpeas.

Figure 2. Grain yields of intercropped sorghum and cowpea in January 1995, with different annual rates of goat manure.



Discussion

Soil chemical and mineralogical data showed that in most aspects, the soils were very similar. The major difference was the soil P, which was much higher at Mutuobare. There was more topsoil SOM-C at Mutuobare, and relative to Machang'a, it was enriched in labile fractions, indicated by (i) the lower radiocarbon age and (ii) the high rate of N mineralization during the rainy season. The extra soil P at Mutuobare therefore influenced soil fertility, not only by its direct effect on plant growth, but by increasing SOM turnover. The native soil P status at Mutuobare not only made growing conditions more favourable to legumes, but it also led to improved N supply by increasing the proportion of labile fractions of SOM.

The native P status of Mutuobare favoured N fixing plants, indicated by (i) the natural mix of tree species in favour of acacias and (ii) the better performance of cowpea crops there. Improvement of the soil P status with manure over the previous six years at Machang'a improved the yields of cowpeas, but it did not increase the legume: cereal ratio. Because of their potential for adding N to the soil, the use of legumes is often regarded as an important aspect of improved cropping systems for tropical smallholder farmers. Intercropping is widely practiced and is a part of farmers' strategy to diversify and thus reduce risk in food production. However, it appears that it is not easy to shift soil conditions in favour of legumes by adding P as manure.

Thus, the native soil P status is an important indicator of the potential of a soil for improvement or rehabilitation.

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A COMPARISON OF METHODS OF CARBON DETERMINATION FOR SOILS OF TRIAL 1

A.N. Micheni, G.P. Warren and F.M. Kihanda

Introduction

Soil organic carbon is the basis for quantifying soil organic matter (SOM) which is an important component in soil fertility. Almost all the soil nitrogen is contained in SOM. and other important aspects of soil fertility related to SOM are moisture retention, cation exchange capacity (CEC) and stabilization of soil aggregates and soil structure. Maintenance of soil microorganisms and their activities are highly influenced by the level of organic matter in the soil. Hence, SOM has an important role in both soil physical and chemical properties.

The amount of SOM depends on both the annual input of organic matter and its rate of decomposition, the latter being highest in hot, humid climatic regions (Rowell, 1994). Plant tissues are the main source of soil organic matter, animal wastes and their remains are secondary compared to what is contributed by plant (Brady, 1990). In arid and semi arid Eastern Kenya, climatic, edaphic factors and the land use systems have much impact on the amount of SOM. Such areas have low and annual rainfall and the soils are generally shallow, sandy or rocky. These factors cause sparse vegetation that gives a low cumulative organic matter input. High temperatures and prolonged drought kill some of the plants or speed up the decomposition and erosion losses of plant tissues, contributing to low SOM.

Because SOM is important to soil fertility, suitable methods are needed to measure it in the Kenya dryland soils.

Materials and methods

Soil samples

In the seven sites of Trial 1 (Appendix 1), there were four in Mbeere District (Gategi, Machang'a, Kamwaa and Mutuobare), and three in Tharaka/Nithi District (Kajiampau, Gacheraka and Kaanyaga). Soil samples were taken in February, 1996 from the three unmanured plots at each site

Except for the return of crop residues, the sampled plots had been cultivated for about 12 seasons (6 years) without application of either organic or inorganic fertility inputs. The samples were taken within the cultivation depth (0 - 15cm) and later oven-dried (105^{0}C overnight). Three methods of C analysis were tested on these soil samples

Carbon determination methods

(i) "Tinsley": The principle of the method is to completely oxidize soil organic matter by heating the sample with a solution of potassium dichromate and sulphuric acid at 135°C for 2 hours. A known amount of dichromate is used, and the excess after reaction is measured by titration with ferrous ammonium sulphate solution.

(ii) "Walkley-Black" In this simplified procedure, soil is treated with hot potassium dichromate and sulphuric acid solution but the temperature is not controlled.

(iii) "Leco" The soil was placed in an automated analyser (LECO instruments model SC444). The sample is heated to 1000°C in a furnace and combustion of the SOM produces CO_2 gas which is measured by infra-red spectrometry.

Table 1: Comparison of Soil Carbon using different methods

	Carbon Determination Method (% Oven Dry unmanured Soil)		
Site	*Walkley-Black*	*Tinsley*	*Leco*
Gategi	0.87	1.23	1.65
Gacheraka	0.61	0.81	1.11
Kaanyaga	0.46	0.61	0.68
Kajiampau	0.52	0.64	0.71
Kamwaa	0.49	0.61	0.72
Machang'a	0.47	0.58	0.71
Mutuobare	0.92	1.11	1.27
Average	**0.62**	**0.80**	**0.98**

Results

The three methods gave mean C contents over all seven sites of 0.62, 0.80 and 0.98 %C for Walkley-Black, Tinsley and Leco, respectively (Table 1). The Tinsley method is the definitive method for organic carbon determination, since almost 100% of organic C is measured. The Walkley-Black method measured only approximately 77% (i.e. $^{0.62}/_{0.80}$)of organic carbon, because organic C is only partly oxidised by this method. A scatter diagram (Figure 1), showed the relationship between Tinsley and Walkley-Black methods, and a good correlation was found. The correlation line was:

$$\textit{Walkley-Black Carbon} = 0.0555 + 0.7162 \times \textit{Tinsley-C}. \qquad R^2 = 0.895.$$

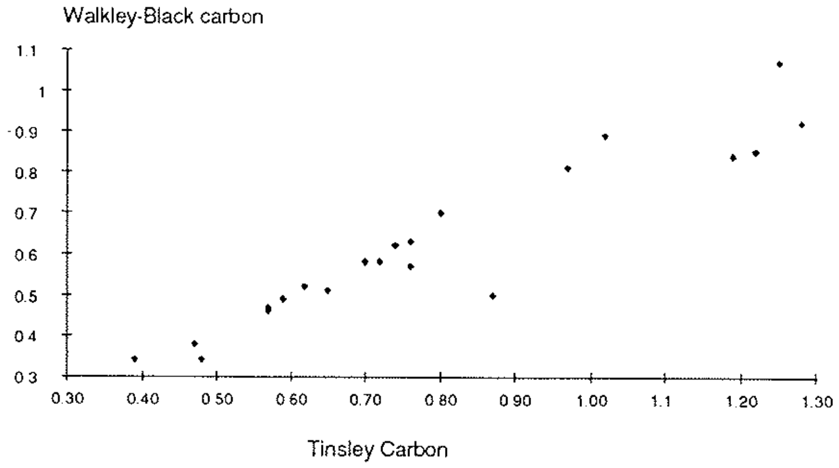

Figure 1. Correlation between Tinsley and Walkley-Black determined soil carbon

The Leco method also measures inorganic carbonates in the soil, which are decomposed at the furnace temperature. Thus both the organic and inorganic C are determined by the Leco method.

The Gategi site which is situated on a vertisol had the highest value for SOM (1.23% organic C). The second in line was Mutuobare with approximately 1.11 %C. The latter site is known to be very fertile because it is rich in available phosphorus. Gategi soil had a much larger difference between Leco-C and Tinsley-C (1.65-1.23=0.42%) than any other soil. It also has a high pH (8.2 in water) and therefore contains free carbonates

Conclusion

The Walkley-Black method is the standard method used at KARI National Agricultural Research Laboratories, Nairobi. Compared with Tinsley, it is much quicker to do. However, the Walkley-Black method measured only approximately 77% of organic carbon (determined using Tinsley). This result is in agreement with the experience that the Walkley-Black method measures about 75% of C in temperate soils (Rowell 1994). Hence, it does not measure all the organic carbon but because it has a good correlation with Tinsley method, it can be used to estimate SOM for dryland soil and is completely suitable for comparisons between soils.

The total C method with the Leco instrument measured all organic C, plus inorganic C. This gave an important difference at higher soil pH. It is however the quickest method and is convenient and precise, if the instrument is available.

Acknowledgement

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NUMERICAL DESCRIPTION OF THE RESPONSE TO MANURE AT THE SEVEN SITES OF TRIAL 1, AND POSSIBILITIES FOR OPTIMISATION OF MANURE RATES.

Introductory Note

The following material was drafted for the Project Workshop, in collaboration with Mr J Ouma, the agricultural economist at KARI Embu RRC who worked on DAREP activities. Unfortunately, Mr Ouma was called to another meeting at the time of the Workshop, and the paper was not completed. It is included in the Final Report because it indicates the additional "adaptive" activities needed to estimate ranges of appropriate manure rates for these soils.

Technical Introduction

Trial 1 had been laid out with three treatments: 0, 5 and 10 t ha^{-1} of manure per year. For most sites and crops, the response to the first 5 t ha^{-1} of manure was more than the response to the second increment of 5 t ha^{-1}. This is a clear case of the "Law of Diminishing Returns": the highest economic return in for manure application will be at a rate less than the rate giving the maximum yield. This is because there comes a point on the response curve when the cost of adding more manure exceeds the value of the extra yield produced. A simple comparison of yields at the two rates of manure does not enable an economic optimum rate of manure application to be estimated, which might perhaps be 2 t ha^{-1} in one soil or 6 t ha^{-1} in another. It is impractical to do a field experiment with every possible rate of manure. In principle, an optimum rate could be estimated if the response to manure in the experiment with few rates could be fitted to a continuous function describing the effect of manure (M) on yield (Y):

$$Y = f(M)$$

This could then be incorporated in a numerical economic model for that soil, enabling the value of the extra yields to be balanced against the work required to acquire and spead the manure. An optimum rate would be one where the profit margin was maximised.

Methods

Comparisons of the yield responses showed that there were significant differences between soils. Sorghum was the crop component which showed up the effects of manure most clearly, but the other crops also responded to some extent, so each soil and crop combination was fitted to a separate curve. There were also differences between seasons. However separate curves for each season were not produced. It is impossible to predict the rainfall of a year, and it is only practical to apply manure before planting. Therefore manure management on the field cannot realistically be modified according to actual subsequent weather conditions. Instead, the equations should represent the response over a longer term, balancing wetter and drier years. For this work, the data fitted were the treatment means and manure rates for each of the three seasons between 1993 and 1996 for which a crop was grown.

Various equations have been used to describe responses to fertilizers and manures, with the quadratic and Mitscherlich (exponential) relationships probably the commonest. In Trial 1, the possible precision was low because of the small number of manure rates, so complex equations could not be used. Instead, a simple square root equation was considered acceptable:

$$Y = a + b\sqrt{M}$$

This shape of this equation is approximately correct as it describes a progressively lower marginal response the higher the manure rate (Figure 1), and is very easy to fit. However, a more realistically shaped curve at the lower rates is given by a quadratic equation, which can also be formulated as a linear plus square root as follows:

$$Y = a + b\sqrt{M} + cM$$

In our case, a study with the complete plot-by-plot data for Machanga site showed no significant improvement in fit if a linear term was included as well, making a quadratic equation. When judged by simple correlation coefficients, the simple square root equation was better than the quadratic for 17 out of the 28 crop and site combinations. For Gategi, a simple linear equation was chosen because the second increment of manure gave bigger yield increases than the first:

$$Y = a + bM$$

For a few cases, with crops representing only a minor part of the yield and giving little or no response to manure, a constant fitted yield was used.

Results and discussion

The tabulated results (Table 1) do not add any further interpretation to the data regarding the fertility differences between soils (Final Report: Appendix 2). Examination of the coefficients for $\sqrt{M}$, where fitted, confirms the strong response by sorghum to manure, all these coefficients being higher than any coefficient of any other crop. Sorghum is therefore the principal beneficiary of the manure application. The response to manure is particularly high in the case of sorghum at Machanga. It would be possible to use the fitted equations to estimate the grain yields from intermediate rates of manure applied. An optimum rate of manure might be the one in which the profit was maximised for the activity of growing crops. This depends on the following factors:

(i) The cost of manure.
(ii) The amount of extra products produced in return for manure application.
(iii) The value of the products produced.

Factor (ii) has now been quantified for a cropping system which is reasonably typical, incorporating the four main food crops of the region and the common practice of intercropping. The relationships given (Table 1) could be used for further economic studies, perhaps with some updating at particular sites to include additional data.

Factors (i) and (iii) require supplementary socio-economic investigations, which were outside the direct scope of the Maintenance of Soil Fertility project, but were intended to be followed up if appropriate funding was obtainable. Studies in the Kiambu area, discussed by Dr Kimani (KARI Muguga: Workshop Proceedings; to be published) showed surprisingly high costs for manure. His figures were the source of significant disussion at the Workshop. However, Kiambu is an area with significant commercial trade in manure. In the case of dryland subsistence farming, monetary costs would be nil, but a value must somehow be placed on the labour required to move the manure to fields, and possibly also on aspects of the housing and management of the animals so as to enable manure to be kept and distributed. Important components of such data, eg farming activity surveys (DAREP reports), monthly surveys of grain prices in markets are available through the economic surveys of DAREP and predecessor projects. In their turn, that work is of little use without the numerical description of how the crop responds to fertility maintenance, to link (i) and (iii). It is proposed that estimates of manure requirements for improved yields should be investigated for different soil types, with typical sets of economic conditions on-farm.

Two environmental assumptions are present in the above proposal: (i) that the yield relationships are stable and (ii) the manure used is the same quality as the Marimanti goat manure used in Trial 1. The field experiments concerned have been farmed under a well-defined system since 1988 or 1989, depending on the site. They had 4 to 5 years cropping before the start of the period for assesssment of the yield-manure relationships. Early indications from modelling work at Rothamsted (using in part data from this project) suggest that the turnover time of SOM in the semi-arid tropics in much faster than in temperate climates, with a turnover period of about 9 or 10 years (compared to over 20 in European conditions). Also, the trends in extractable soil P showed much less change over 1993 to 1997 than in the previous 4 or 5 years. It is suggested that a large part of the rapid change that follows land clearance had occurred by 1996. Although the experiment was not yet at a dynamic equilibrium regarding soil fertility turnover, the relationships developed from that time onwards could be acceptable for practical purposes over a timescale in excess of 10 years. Regrettably, the sites are now lost.

The manure used was analysed for major nutrients every year from 1993 to 1996, and it was of a high and uniform quality in terms of nutrient and C content, because it was collected from a closely-managed and well constructed animal house at a research station. Manure from dryland farm *bomas* is very variable (Probert et al. 1995, Kihanda 1996). To use the relationships for typical farmyard manures, some adjustment is needed to account for the lower nutrient contents of the latter. The C/N ratio was the best indicator of N supply in manures collected from Embu District (Kihanda, 1996), so adjustment based on that ratio might be appropriate. To achieve this effectively, it would be desirable to control manure quality, paticularly by storage conditions, and to identfy suitable manure C/N values according to animal and farm conditions.

Conclusion

Relationships between the manure applied and grain yields varied between soils and crops. The data could be used to estimate optimum rates of manure for the different soils. This would require extra economic and farming information. An adaptive project fully involving economic approaches would be able to develop realistic recommendations.

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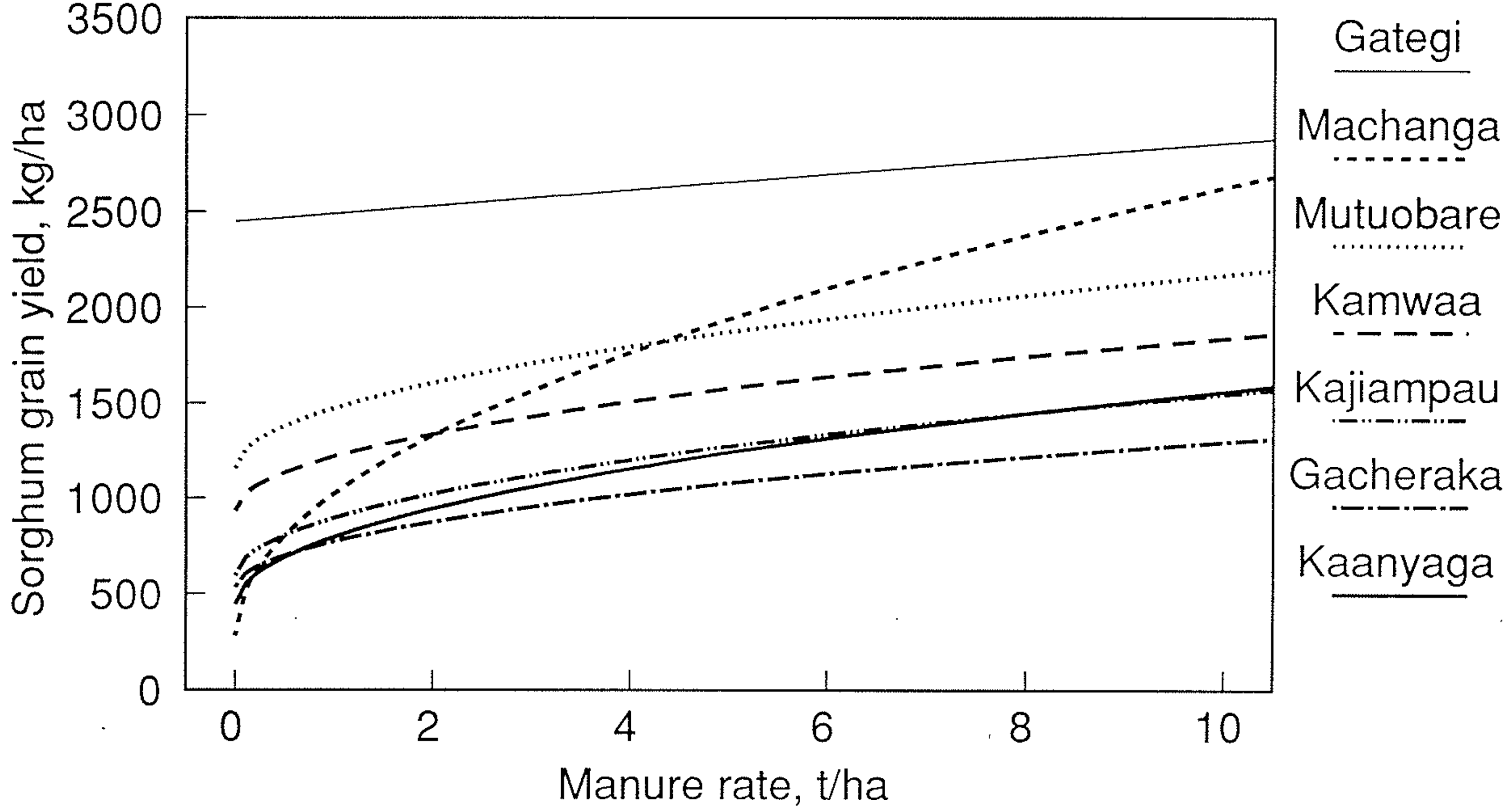
Table 1. *Fitted equations describing the grain yields (Y, kg ha^{-1}) in relation to annual manure application rate (M, kg ha^{-1}) for each crop, averaged over three years, from the November 1993 season to the April 1996 season.*

Sorghum	Gategi:	Y = 2449.7 + 0.0405 M
	Machanga:	Y = 281.0 + 23.44 √M
	Mutuobare:	Y = 1153.8 + 10.13 √M
	Kamwaa:	Y = 932.8 + 8.68 √M
	Kajiampau:	Y = 597.0 + 9.11 √M
	Gacheraka:	Y = 535.5 + 7.22 √M
	Kaanyaga:	Y = 445.7 + 10.78 √M
Cowpea	Gategi:	Y = 168.4 + 0.0029 M
	Machanga:	Y = 24.0 + 2.96 √M
	Mutuobare:	Y = 835.9 + 1.23 √M
	Kamwaa:	Y = 562.2 + 5.06 √M
	Kajiampau:	Y = 1111.8 + 3.79 √M
	Gacheraka:	Y = 741.9 + 5.06 √M
	Kaanyaga:	Y = 841.6 + 3.28 √M
Millet	Gategi:	Y = 182.4 + 0.0525 M
	Machanga:	Y = 95.9 + 5.89 √M
	Mutuobare:	Y = 520.6
	Kamwaa:	Y = 561.5 + 7.07 √M
	Kajiampau:	Y = 692.6 + 5.56 √M
	Gacheraka:	Y = 431.5 + 2.76 √M
	Kaanyaga:	Y = 117.5 + 3.22 √M
Green Gram	Gategi:	Y = 405.0 + 0.0085 M
	Machanga:	Y = 12.4 + 1.21 √M
	Mutuobare:	Y = 654.7
	Kamwaa:	Y = 88.1 + 1.19 √M
	Kajiampau:	Y = 251.9
	Gacheraka:	Y = 165.8 + 1.04 √M
	Kaanyaga:	Y = 121.9 + 2.00 √M

Figure 1. Fitted response curves for the effect of manure on sorghum grain yield at the Trial 1 sites, averaged over 1993 to 1996.



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SOIL FERTILITY ASSESSMENT IN FARMERS' FIELDS IN THE PROJECT AREA

Reprinted from the conference paper in Kangara, Sutherland and Gethi 1997 (Eds.). Proceedings of the conference on participatory dryland agricultural research east of Mount Kenya, January 21-24, 1997. KARI: Kitale, Kenya.

AN APPRAISAL OF SOIL FERTILITY IN SMALLHOLDER FARMS IN THE SEMI-ARID AREAS OF THARAKA NITHI DISTRICT: FARMERS' ASSESSMENT COMPARED TO LABORATORY ANALYSIS

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ABSTRACT

A participatory appraisal of soil fertility status was conducted by a team of agricultural research and extension staff in the semi-arid areas of Tharaka-Nithi district in 1993. The exercise was to assess the soil fertility status of the smallholder farms as experienced by farmers and identify the major soil quality limitations. This was done by farmers identifying the poor and good fields of their farms. In addition to soil fertility management histories for each field, a composite soil sample was taken from the plough layer (0-10 or 15cm). A total of 62 soil samples were taken from 30 farms in 2 villages. The soils were analyzed for extractable phosphorus (Olsen method), total carbon and pH (H_2O and 0.01M $CaCl_2$). The overall mean for extractable soil P was 10.7 mg/kg. However, there was a wide variation with values ranging from 1.6 to 53 7 mg/kg. Total soil carbon mean was 0.60 % and soil pH was around neutral. The laboratory analysis results generally agreed with the farmers experiences in categorizing the land quality within their farms.

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INTRODUCTION

In Kenyan arid and semi-arid areas which comprise about 80% of the total land area, low levels of soil nitrogen (N) and phosphorus (P) significantly limits crop production (Siderius and Muchena, 1977; Okalebo *et al.*, 1992). Soils of semi-arid Eastern Kenya are also reported to be low in organic matter (Ikombo, 1984). Low soil fertility was ranked second to water as the most important constraint limiting crop productivity in the semi-arid areas of Tharaka-Nithi District (DAREP,1995). Therefore, improvement and maintenance of soil fertility is of fundamental importance, particularly at the farm level.

The objective of the present study was to assess soil fertility as perceived by farmers in the semi-arid areas of Tharaka-Nithi District and to compare their assessment with selected laboratory analysis. This was envisaged to give an insight

into the farmers' perception of soil fertility and eventually help in developing sustainable soil fertility management techniques that would lead to enhanced crop productivity. A complementary study deals with a wider range of soil properties at selected on-station experimental sites in the area.

MATERIALS AND METHODS

Diagnostic farming systems survey was conducted by a multi-disciplinary team of agricultural research and extension staff in the semi-arid areas of Tharaka-Nithi District from 15th November to 3rd December, 1993. A participatory appraisal of the soil fertility status in 30 farms located at Gatunga (16 farms) and Kamaguna (14 farms) areas was conducted alongside the survey. Farmers were asked to choose two fields, one they considered to be of good fertility and another of poor fertility. The farmers' assessment of soil fertility was based mainly on crop vigour, presence of certain weeds, presence of earthworms and soil colour.

Sixty two soil samples were randomly taken from the plough layer (0-15cm) in several spots (5 to 10 spots) within the selected fields, mixed well on the spot and a composite sample of about 1 kg taken. Information on the cropping history of the fields was also recorded, along with site and farm information.

The soil samples were air-dried and ground by hand to pass through a 2 mm mesh sieve. Sub-samples were taken for total C, pH and extractable P determination. Total carbon analysis was done by combusting 0.3 g of an air-dry soil in oxygen at 1400°C in a Leco Corporation model SC-444 total combustion analyzer, in which the CO_2 produced is measured by infra-red absorbance. In case of extractable P, sodium bicarbonate was used as the extractant (Olsen *et al.*, 1954). Soil pH was determined at a soil: solution ratio of 1:2.5 (water and 0.01M $CaCl_2$) using a conventional glass electrode. The Laboratory analysis was done at both Regional Research Centre, Embu, Kenya and Soil Science Department, University and of Reading.

Analysis of variance (ANOVA) was done using "Instat" statistical package to compare the two areas and look at the general distribution and range of results.

RESULTS

General Observations

The records taken alongside the soil sampling showed that all farmers except one do not use inorganic fertilizers or manures. Only one farmer reported to incorporate crop residues at ploughing. Shifting cultivation or fallowing was being practised by majority of farmers to restore soil fertility. Soil erosion was also reported especially on sloppy fields though most fields were flat to gentle sloping. Soils were well drained sandy loams. Crops grown were mainly sorghum, millets, maize, cowpeas, greengrams, pigeonpeas, cassava and cotton.

Extractable Phosphorus, Total Carbon and pH of the Soils

Extractable P. The overall mean for soil extractable P was 10.7 mg/kg. However, there was a very wide variation with P values ranging from 1.6 to 53.7 mg/kg. There was no significant difference between the Gatunga and Kamaguna areas in soil extractable P.

The two samples with over 30 mg/kg of extractable P were not included in the ANOVA thus reducing the coefficient of variation from 67% to 37.3%. This resulted in highly significant differences between farms (Tables 2 and 3). However, there were no differences between the two survey areas (Table 1). These results therefore suggests that soil available P can vary a lot over distances of a few kilometres depending on the density of farms in the survey areas. However the means over all farms represent the study area fairly well. There was a strongly significant difference between the good and poor soils as selected by the farmers (Tables 2 and 3).

Table 1. Differences between Gatunga and Kamaguna areas in Olsen-P, Leco and pH

Area	Olsen-P mg/kg	Leco-C %	pH (H_2O)	pH ($CaCl_2$)
Gatunga	10.52 (1.53)	0.808 (0.044)	7.40 (0.09)	6 70 (0 10)
Kamaguna	10.98 (1.69)	0.350 (0.049)	7.60 (0.10)	6 86 (0.12)
F-ratio	0.0	48.7	2.0	1.1

Note: Standard errors are shown in brackets. *** differences between zones significant at the 1% level.

Total C. The distribution of soil C concentration appeared tighter than for extractable P. The general mean of 0.60% indicated that soil organic matter concentrations were low throughout the farms visited. However, in contrast to extractable P results, there were highly significant differences between the Gatunga and Kamaguna areas (Table 1). Around Kamaguna,average total C was very low, 0.35%. There were highly significant differences in total C both between farms and between good and poor soils (Tables 2 and 3).

pH. All soils were neutral in character with a mean soil pH of 7.49 and 6.78 in water and 0.01M $CaCl_2$, respectively. There were no significant differences between the two areas, farms and even between good and poor soils (Tables 2 and 3), so farmers' judgement of fertility did not depend on pH.

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Table 2. F ratios indicating the occurrence of significant differences between farms and soil quality classes for Olsen-P, Leco-C and pH.

Contrast	Olsen-P mg/kg	Olsen-P* mg/kg	Leco-C %	pH (H_2O)	pH ($CaCl_2$)
Between farms	1.6	4.0**	13.3**	1.6	1.5
Soil quality	8.9**	11.8**	30.4**	0.2	0.1
C.V (%)	67.0	37.3	21.0	6.6	8.1

Table 3 Olsen P, Leco-C and pH and poor soil.

Soil Quality	Olsen-P mg/kg	Olsen-P* mg/kg	Leco-C %	pH (H_2O)	pH ($CaCl_2$)
Good	14.1	11.8	0.673	7.52	6.79
Poor	8.2	8.3	0.495	7.46	6.74
SE mean	1.39**	0.72**	0.023**	0.09	0.10

Note: A data excludes the 2 farms where there were samples with >30 mg/kg of Olsen-P
* differences significant at the 5% level. *** differences significant at the 1% level.
*data excludes the 2 farms where there were samples with >30 mg/kg of Olsen-P.

DISCUSSION

Phosphorus

Reports on extractable P using the Olsen method indicate that crop response to fertilizer has been observed in soils of semi-arid areas where P test levels are below 10 mg P/kg soil (Okalebo *et al.*,1993). For general interpretation of extractable Olsen P , El-Swaify *et al.*, (1985) reported the critical Olsen P levels for the Alfisols of semi-arid India as follows: 0 -5 ppm, low; 5-10 ppm, medium; and >10ppm, high. Using this criteria, the farmers' good soils were on average adequately supplied with P. Soils classified as poor by farmers were of medium fertility on average and most crops should respond to P fertilizer. However, there was great variability between farms such that soils classified as poor contained some samples "high" in P (>10 mg/kg). This probably happened because farmers assessed the soil fertility only within their own farms and secondly, other nutrients like N or poor soil physical conditions may be more limiting in many farms. This makes it difficult to use farmers' assessments of soil fertility as a guide to choosing appropriate cropping packages or remedial fertility treatments on a wider scale.

Extractable phosphorus varied a lot from farm to farm, and differences between farms in productivity are partly due to differences in soil P supply. These findings are in agreement with those of Okalebo *et al.*(1992).

Organic matter and Nitrogen

Potential soil N supply is related to the soil organic matter since its mineralization is one source of available N. Organic C can also give some indication of the potential soil N supply because the ratio of C:N is remarkably constant at around 10:1 and 12:1 in most soils (Brady,1990). Thus the variations in Leco-C suggest that soil N supplies can be expected to vary between farms, fields within farms as well as between different areas. Since mean Olsen-P was not significantly different between Gatunga and Kamaguna, the soil N supply may be a critical limitation to crop productivity in Kamaguna.

According to Tekalign (1991) as quoted by Okalebo *et al.*(1993), the general guidelines for interpretation of soil carbon test results are as follows: < 0.5%, very low; 0.5 - 1.0%, low; 1.0 - 2.0%, moderate; 2.0 - 4.0%, adequate; and >4.0, high.

Results therefore indicated that the majority of soils sampled (55%) fall into the very low category. Therefore, clearly perceived, inadequate soil fertility could be linked to the low soil organic matter levels prevailing.

It is likely that soil organic matter can also vary a lot between farms as well as between zones since erosion events and land use will locally diminish organic C (Okwach *et al.*,1992), creating farm-to-farm variations. In any case, the differences between good and poor soil on the same farm may affect the use of particular fields for productive purposes. The differences in soil organic matter revealed here are therefore, likely to be very important in controlling yields obtainable without fertilizer N inputs.

Soil pH

Since soils are generally close to neutral, a wide range of arable crops could be grown in the survey area without any problem. The neutral pH also means that use of acidifying fertilizers like diammonium phosphate would be an acceptable practice but only in the short to medium term.

RESEARCH PRIORITIES

Results indicated that total C is the measured soil property that related most closely to farmers' assessment of soil fertility. The present study,therefore, indicate that the first priority for soil research should be to look for ways of improving the levels of organic matter. Consequently, more effort should be geared towards the improvement of manure and crop residue management at the farm level. This would ensure a sustainable maintenance or enhancement of soil fertility for increased crop productivity.

It would also be worthwhile to capitalize on the good P availability at some locations by judicious use of N fertilizer, since if the location is high in P supply, the response to N is expected to be good. Legume use could also be maximised in P fertile locations since these crops are able to supply their own N.

The neutral soil pH suggests that other factors allowing a wide range of arable crops can be grown in the survey area without any problem. There should also be good potential for making use of microbial processes such as N fixation and utilization of P uptake by mycorrhizal associations.

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CONCLUSIONS

Farmers' perception of soil fertility based largely on practical experience of cropping, depends strongly on the concentration of soil organic matter present. Averaged over all farms, farmers' information and knowledge of soil quality and fertility corresponds well to assessments of soil C and P status. However, the variable nature of soils means that farmers' assessments are only applicable on a local basis. Therefore, the choice of a good cropping system may not automatically flow from "indigenous knowledge" since one farmer's fertile soil may often be another's poor soil and vice versa.

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ANALYSIS OF SOIL ORGANIC CARBON AND QUALITY CONTROL

SS Atwal and GP Warren

Introduction

The aim of the Project was to assess trends in soil fertility over time, ie. the duration of the project. Samples were taken every year and analysed. Because we were looking for small changes against a background of large variability it was exceptionally important that there was no bias or drift (or at least as little as possible) in the analytical methods used, since the work was spread over five years. The method used for soil organic C is described in some detail here. Similar quality control procedures were adopted for the soil total N and soil extractable P determinations.

Method

About 0.5g of soil is accurately weighed to 3 decimal places, into 100ml Tecator digestion tubes, followed by 20.00ml of the digestion mixture (potassium dichromate, sulphuric acid, orthophosphoric acid). A batch of 40 tubes, including 3 blanks, 1 standard soil and 36 soils are placed in a Tecator Digestion block, which is preheated to 130-135 degrees centigrade. This temperature is maintained for 2 hours after which the tubes are removed from the digestion block. During the heating, a redox reaction takes place, whereby the dichromate is reduced and the organic Carbon is oxidised.

The excess dichromate which does not take part in the redox reaction, is determined by titration with a solution of ammonium ferrous sulphate. The ammonuim ferrous sulphate is first standardised by titrating with a 'cold blank' of the oxidising solution. Then the 'hot blanks' are titrated to to check that none of the dichromate has decomposed by excess heating. Finally the internal standard and soils are titrated. From this, the amount of dichromate used up in the reaction to oxidise the organic carbon is determined, and knowing the stoichiometry of the redox reaction, the % organic carbon in the soil can be determined.