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Testing the APSIM Model with Experimental Data from the Long-term Manure Experiment at Machang'a (Embu), Kenya

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Abstract

A 27 season, long-term study (1989–2002) was conducted at Machang'a, near Embu in the semi-arid lands of eastern Kenya, to assess the effect of manure application on soil nutrient status and crop productivity. The experimental treatments comprised a control (no inputs); 5 and 10 t ha^{-1} rates of high quality manure (26% C; 2.0% N; 0.48% P) from a single source and applied annually in October; residual manure treatments where manure application ceased from 1993; and a NP fertiliser treatment on previously unfertilised plots from 1993. The data from this experiment have been used to test the performance of the Agricultural Production Systems Simulator (APSIM) in predicting the crop dry matter yield, extractable soil phosphorus and soil organic carbon on a P-deficient soil. The experiment was simulated using the APSIM P-aware maize module, even though maize was not the test crop before the November 1999 season. Agreement between model predictions and measured data was generally satisfactory for all three of the variables tested.

The APSIM modelling framework described elsewhere in these proceedings now has a capability to simulate the dynamics of phosphorus in addition to nitrogen, and the effects of both nutrients on crop growth (Probert 2004). In order to validate that the model predictions are credible, there is a need to compare the model outputs against measured data. Unfortunately, few studies have been carried out in the tropics that provide suitable data sets for such purposes.

In this paper, we describe an experiment that does provide suitable data for testing the model, and to allow comparison of the observed data with model predictions.

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The Experiment

Field site

The experimental site was at Machang'a, Mbeere District (0°47'S, 37°40'E; 1060 m above sea level), approximately 200 km northeast of Nairobi. The soil is a chromic Cambisol containing 56% sand, 13% silt and 31% clay, with pH (in water) 6.55 (Warren et al. 1997). These soils are deficient in nitrogen and phosphorus (Siderius and Muchena 1977; Warren et al. 1997). The site was cleared from native bush at the end of 1988 and cropping began in March 1989. There are two cropping seasons, which we identify by the month of peak rainfall; these are the 'November season' from October–January (in Kenya commonly referred to as the 'short rains') and the 'April season' from March–June (the 'long rains').

Experimental design and treatments

The original design (Gibberd 1995) was a complete factorial of three cropping systems by three manure treatments (0, 5 and 10 t ha^{-1}), with the manure applied annually in October. In February 1993, all plots were sampled and it was found that the different crop rotations had not caused any significant effects on soil organic C, total N, extractable P or exchangeable cations (Warren et al. 1997). Subsequently, the rotation treatments were discontinued and new treatments introduced to study residual effects of manure and the effect of fertiliser applied to every crop (Table 1). Manure and fertiliser were broadcast and incorporated during cultivation before sowing (cultivation depth 0.15 m).

The manure was acquired from a single source (Goats and Sheep Project at Marimanti, Tharaka District) where flock management remained the same throughout the experiment. Average composition of the manure (dry matter basis) was 25.6% C, 2.04% N, 0.48% P (C:N = 12.7).

Crops and management

Before 1993, the cropping systems comprised rotations of sole legume and cereal crops and legume/ cereal intercrops. The crops alternated between (i) sorghum *(Sorghum bicolor*) and cowpea (*Vigna unguiculata*), and (ii) pearl millet *(Pennesitum typhoides*) and green gram (*Vigna radiata*). After the experimental design was changed in 1993, the cropping system became sorghum/cowpea intercrop for the November season and millet/green gram intercrop for the April season, which closely follows local farming practice. Starting with the November 1999 season, all plots were cropped to maize (*Zea mays,* var. Katumani composite B) in both seasons. Sowing of all crops was done at the start of the rains. Other agronomic practices were carried out at appropriate times using hand tools for cultivation and weeding. All plant materials except the grains were returned to the respective plots at the end of every season. The above-ground biomass was cut at ground level, residues chopped into small portions and incorporated into the soil during land preparation for the succeeding cropping seasons. Crop biophysical, soil nutrient characterisation and meteorological data were collected.

Soil sampling and analysis

Regular sampling of the soil (0–20 cm) began in 1993. Sampling was done either in February or September, before cultivation and incorporation of residues and manure. Soil was subsampled, air-dried, ground < 2 mm sieve and analysed for: extractable P (Olsen method; 0.5 M $NaHCO_3$, adjusted to pH 8.5); organic C by heating for 2 hours at 130–135° C with H_2SO_4 / H_3PO_4 / $K_2Cr_2O_7$ mixture (Anderson and Ingram 1993).

Simulations

The maize module is currently the only crop module available in APSIM that is ‘P-aware’, meaning that it has the necessary routines to constrain crop growth under P-limiting conditions (Probert 2004). We have therefore simulated the whole experimental period assuming that sole maize was planted every season (sowing dates 14 October and 18 March; 4 plants m^{-2}). Manure was applied and incorporated on 2 October each year and fertiliser applied at sowing. Cultivations before sowing incorporated all residues from the previous crop.

Table 1. Soil fertility treatments used in the long-term experiment at Machang’a.

Treatment	1989–1992	1993–2001
Control	None	None
A1	5 t ha^{-1} y^{-1} manure[a]	5 t $ha^{-1}y^{-1}$ manure
A2	10 t ha^{-1} y^{-1} manure	10 t $ha^{-1}y^{-1}$ manure
B1	5 t ha^{-1} y^{-1} manure	None
B2	10 t ha^{-1} y^{-1} manure	None
F	None	NPK fertiliser (51, 12, 30 kg ha^{-1}) every season[b]

[a] Manure applied annually in October.
[b] From November 1993; these rates provide same annual inputs of N and P as the 5 t ha^{-1} manure treatment.

The simulations for each treatment were carried out as a single run, with all treatments initialised with identical inputs on 1 October 1989. Soil carbon in the surface 0–20 cm layer was based on the measured data in 1993, with an assumption that it declined in deeper layers (soil C deeper than 0.4 m was assumed not to mineralise). Soil labile P was initialised using the measured Olsen P data from the control treatment in 1993 and a factor of 2.5 to convert Olsen P (mg kg^{-1}) to labile P (see below for discussion of the relationship between labile P as conceptualised in the model and soil P test values).

The soil profile had been sampled to determine bulk density and gravimetric soil water when dry (to estimate crop lower limit, LL) and also when wet (to estimate drained upper limit, DUL). However, using these values in the simulation tended to over-predict crop yields. The DUL values were obtained following two weeks of wet weather with 40 mm rainfall on the day before sampling. It is surmised this may have over-estimated the soil's plant available water capacity (PAWC). For the simulations shown below, smaller values of DUL have been assumed, with the rooting depth set to 0.8 m, resulting in PAWC of 92 mm. The soil parameters used for the simulation are set out in Table 2.

Results and Discussion

The mean annual rainfall during the experiment was 796 mm, while seasonal rainfall ranged from 100 to 1030 mm (Figure 1).

Crop yields

In presenting the crop data, emphasis is placed on the total above-ground DM yields since this procedure offers the best chance of minimising any effects of the actual crops grown, and whether grown as sole crops or intercrops. The measured and simulated yields are shown in Figure 2.

In most seasons, observed crop growth responded strongly to inputs of manure, though there were several seasons when yields were very poor for all treatments (April 1992, 1999, 2000; November 1998). There was little difference in yields between the 5 t ha^{-1} and 10 t ha^{-1} rates of manure.

Table 2. Soil properties used for initialisation of the simulation of the Machang'a experiment.

Layer no.	1	2	3	4	5	6
SoilWat parameters [a]						
Layer thickness (mm)	200	200	200	200	200	200
Bulk density (g cm^{-3})	1.28	1.27	1.31	1.31	1.31	1.31
SAT	0.42	0.42	0.43	0.43	0.43	0.43
DUL	0.25	0.27	0.27	0.27	0.26	0.26
LL15	0.13	0.14	0.15	0.16	0.16	0.16
Maize parameter						
LLmaize	0.13	0.14	0.15	0.18		
SoilN parameters						
organic C (%)	0.59	0.50	0.40	0.38	0.36	0.36
finert[b]	0.50	0.90	0.99	0.99	0.99	0.99
fbiom	0.02	0.015	0.01	0.01	0.01	0.01
nitrate-N (mg kg^{-1})	1.25	0.75	0.5	0.5	0.5	0.5
ammonium-N (mg kg^{-1})	0.8	0.35	0.2	0.2	0.2	0.2
SoilP parameters						
labile P (mg kg^{-1})	2.5	2.5	1.0	0.8	0.5	0.5
P sorption (mg kg^{-1})[c]	94	200	200	200	200	200

[a] The soil water balance is described in terms of the volumetric water content at saturation (SAT), drained upper limit (DUL), and lower limit of extraction by the crop (LL); BD is soil bulk density; SWCON is the proportion of water in excess of DUL that drains in 1 day.
[b] finert is the proportion of soil carbon assumed not to decompose; fbiom is the proportion of decomposable soil carbon in the more labile soil organic matter pool.
[c] P sorbed at 0.2 mg L^{-1} in solution.

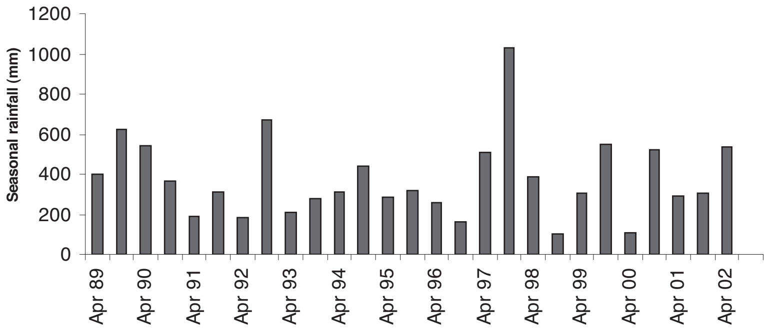

Figure 1. Total rainfall for the 'April' (March–June) and 'November' (October–January) seasons at the site during the experiment.

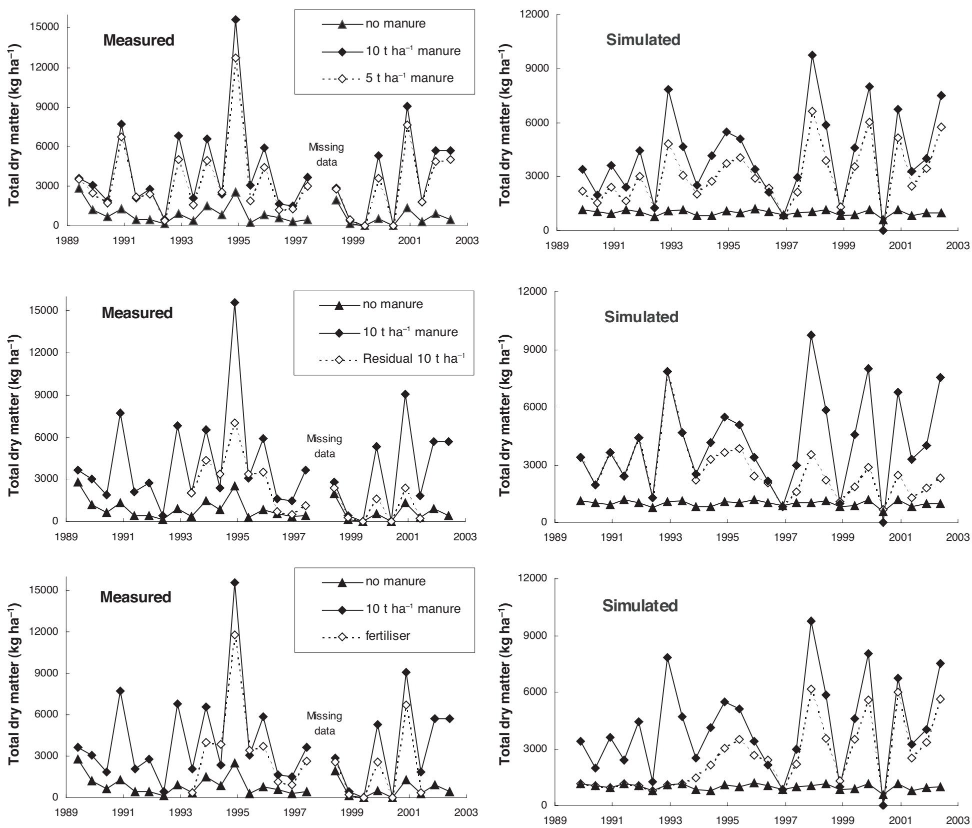

Figure 2. A comparison of the measured and predicted dry matter yields during the experiment. The measured data are in the left-hand panes, the corresponding simulated results in the right-hand panes. The top panes show the treatments that received 0, 5 or 10 t ha^{-1} of manure; beneath are shown the effects of the 10 t ha^{-1} residual treatment (application ceased from 1993) and the NP fertiliser treatment (begun 1993) with the 0 and 10 t ha^{-1} of manure treatments repeated for scaling purposes.

After manure application ceased from 1993, the residual effect from manure declined and yields were only marginally better than the control in the later years of the experiment. Fertiliser application commencing from the November 1993 season increased yields to levels similar to those of the manure treatments.

This overall pattern in the observed yield data was captured reasonably well by the model. In particular, there was conformity in terms of: (i) the yields for the no-manure treatment were typically 1–2 t ha^{-1} though, in contrast to the observed data, the simulated yields exhibited much less season-to-season variation and were never close to zero; (ii) yields with manure were 3–8 t ha^{-1} with only small differences between the 5 and 10 t ha^{-1} rates of manure; (iii) the declining effect from the residual manure treatment; (iv) the response to the fertiliser treatment; (v) crop failures in April 1992, 2000 and November 1996, 1998 seasons when yield for treatments with nutrient input was similar to the no-manure treatment. The largest discrepancy is for the November 1994 season when observed yields of sorghum for all treatments were unaccountably high. The model output permits examination of the stresses (water, N or P) that were limiting to growth. For the control treatment, the dominant nutrient stress in all seasons was predicted to be due to P (data not shown).

The agreement between measured and predicted DM yields displayed in Figure 2 is despite the fact that the maize model is being used for the simulation when other crops were grown. From the November 1999 season this was no longer the case, with maize being grown. Figure 3 summarises the results for these crops. The correlation between observed and predicted yield is high and without any obvious bias.

Soil P

The frequent sampling and analysis for extractable P provides an opportunity to test another component of the model, namely the predicted changes in labile P through time and in response to inputs of P as fertiliser or manure. Conceptually, labile P as defined in the model does not equate directly to any soil P test (Probert 2004). However, it might be expected that, on a given soil, labile P would be proportional to some suitable soil test, so that the soil test values become the means of initialising the model and of testing the sensibleness of the output.

The simulated labile P (expressed as kg ha^{-1}) is compared with the measured Olsen P (mg kg^{-1}) in

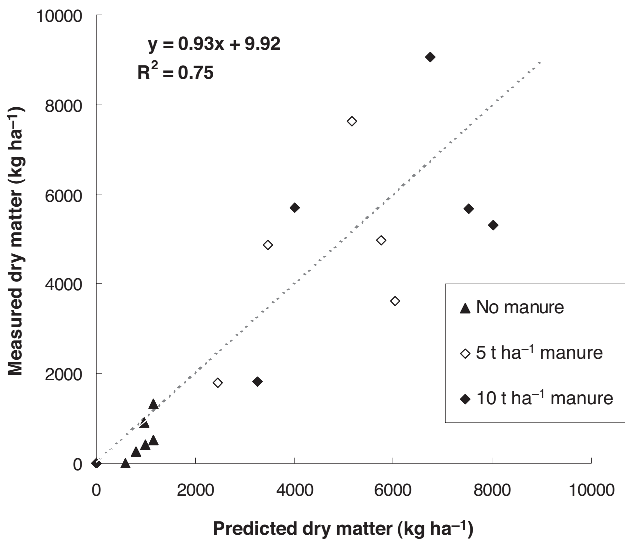

Figure 3. Comparison of measured and predicted dry matter yields of maize for seasons from November 1999. The dashed line is the 1:1 relationship. The fitted linear regression equation and correlation coefficient are given in the figure.

Figure 4. In these graphs, note that the proportionality between the two variates is the same for all of the treatments. For the control treatment, there is little change in P status during the experiment. The trends in the Olsen P data are well matched by the model for the 10 t ha^{-1} manure treatment and the fertiliser treatment (though with much greater variability in the Olsen P data for the manure input). For the 5 t ha^{-1} manure treatment the model over-predicts the Olsen P data, while for the residual treatment the measured Olsen P data decline more rapidly than the simulated labile P.

As presented in Figure 4, the factor between labile P and Olsen P, when adjusted for units, is approximately 2.5, which is the justification for how the labile P pool was initialised for the simulations.

Soil carbon

The simulated and measured soil organic C data are displayed in Figure 5. The agreement looks particularly good for the two treatments that differ most in soil C, and the model simulated well the difference that evolved between the control and 10 t ha^{-1} manure treatment. For the other treatments the agreement is less impressive, though the direction of the trends is well captured by the model. The measured difference in soil C between the 5 and 10 t ha^{-1} manure treatments was less than predicted. Also, the measured decline in soil C after manure application ceased was less rapid than predicted by the model, though there was close agreement at the end of the experimental period in 2002. For the fertiliser treatment, the model agreed with the measured data in that soil C increased compared with the control, but the increase was under-predicted. The change in soil C in the fertiliser treatment must occur as a result of greater crop growth and thus higher returns of crop residues and roots, since there are no direct inputs of C associated with this treatment.

Conclusions

The Machang'a experiment is a long-term experiment, on a P and N-responsive site. The experiment has studied the response of crop growth to inputs of nutrients as manure and fertiliser. Furthermore, it has documented the changes in the soil organic C and Olsen P as well as crop yields. The results of the experiment therefore provide a valuable data set against which several aspects of the APSIM model can be tested.

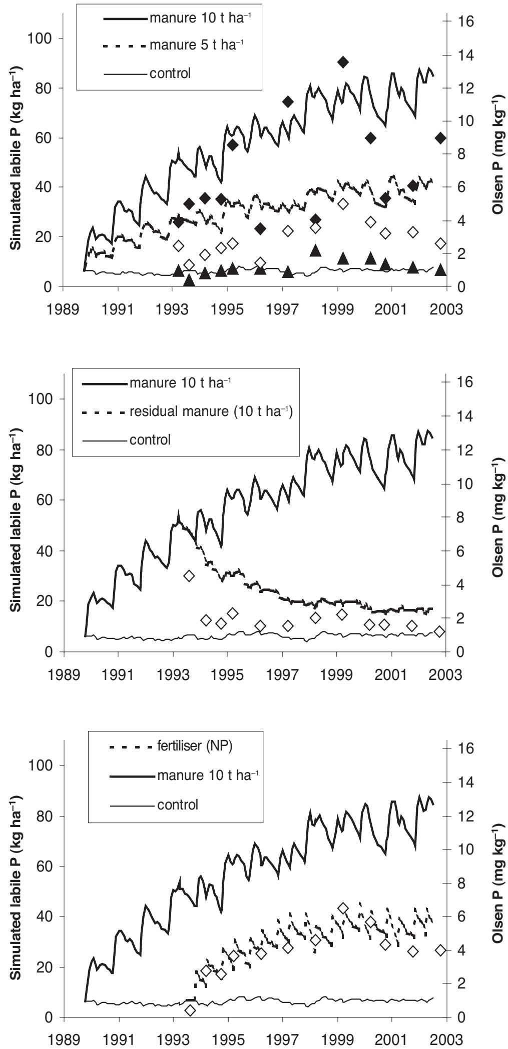

Figure 4. Comparison of simulated labile P (lines) in the surface 0–20 cm layer with the measured Olsen P data (symbols). Note that the two variates are plotted on different scales, but the proportionality between them is identical in the three panes. The top pane shows the 0 (▲), 5 (◇) and 10 (◆) t ha^{-1} of manure treatments; the lower panes show the residual 10 t ha^{-1} of manure treatment and the NP fertiliser treatments with the simulations for 0 and 10 t ha^{-1} of manure treatments repeated for scaling purposes.

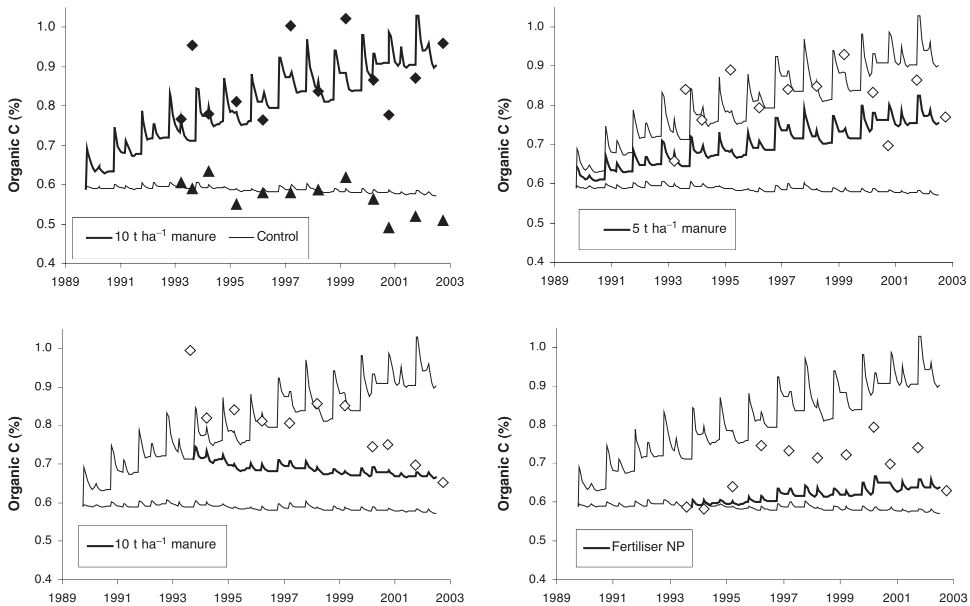

Figure 5. Comparison of simulated soil organic C (lines) in the surface 0–20 cm layer with the measured data (symbols). The top-left-hand pane shows the 0 and 10 t ha^{-1} of manure treatments; in the other panes the simulated results for these treatments are repeated (for scaling purposes) together with the simulations and measured data for the 5 t ha^{-1} of manure treatment, the residual 10 t ha^{-1} of manure treatment, and the NP fertiliser treatment.

The manure source used in the experiment was from a single source throughout the experiment, and was of high quality and therefore may be expected to be a good source of N and P.

The model performance was tested in terms of:

1. *Dry matter yields*. To model the experiment, it was necessary to use the APSIM maize module as a surrogate for other crops that were grown in the early years of the experiment. In recognition of this, we have focused only on the dry matter production. It would be inappropriate to dwell on discrepancies between the observed and predicted yields; rather the focus should be on the ability of the model to capture the trends. The model captured reasonably well the patterns and trends due to treatments and seasons. For the most recent seasons, when maize was the test crop, there was close agreement between observed and predicted yields.

An issue that arises in the interpretation of the output of the model is whether P or water stress is the factor determining growth. For the seasons where there was no difference in yield between the different treatments, it seems probable that water was the limiting factor. This is supported by the low rainfall in these seasons, as shown in Figure 1. However, in the model, P uptake is very dependent on soil water content, so that in these dry seasons the model predicts that P uptake is impaired and P stress becomes important for crop growth. Further testing of the model to explore this matter would require experimental data for a range of P treatments.

2. *Soil P*. The pattern of labile P simulated in the model was very similar to that of Olsen P. On this soil type, the proportionality between Olsen P and labile P (as simulated) was found to be approximately 2.5.

3. *Organic carbon*. The model predicted well the difference between the treatments with and without manure. Other aspects of the simulated soil C, such as the difference between the 5 and 10 t ha^{-1} manure treatment, the decline of soil C in the residual manure treatment, and the magnitude of the increase in soil C when fertiliser was applied, were not so well predicted.

The conformity between simulated and measured data for the crop biomass and soil properties is encouraging. A fuller test of the model's capability to simulate grain yields under P-limiting conditions requires P-aware versions of APSIM modules for the different crops.

Acknowledgments

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References

Anderson, J.M. and Ingram, J.S.I. 1993. Tropical Soil biology and fertility: a handbook of methods. Wallingford, UK, CAB International.

Gibberd, V. 1995. Yield responses of food crops to animal manure in semi-arid Kenya. Tropical Science, 35, 418–426.

Probert, M.E. 2004. A capability in APSIM to model P responses in crops. These proceedings.

Siderius, W. and Muchena, F.N. 1977. Soils and environment conditions of agricultural research stations in Kenya. Nairobi, Kenya, Ministry of Agriculture Miscellaneous Soil Paper No. M5.

Warren, G.P., Muthamia, J. and Irungu, J.W. 1997. Soil fertility improvements under manuring in semi-arid Lower Embu and Tharaka-Nithi. In: Fungoh, P.O. and Mbadi, G.C.O., ed., 1997. Focus on agricultural research for sustainable development in a changing economic environment. Proceedings of the 5th KARI Scientific Conference, Nairobi, 14–16 October 1996. Nairobi, Kenya Agricultural Research Institute, 151–163.