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Evaluation of APSIM to Simulate Maize Response to Manure Inputs in Wet and Dry Regions of Zimbabwe

P. Chivenge,* J. Dimes,† N. Nhamo,§ J.K. Nzuma¶ and H.K. Murwira*

Abstract

This study evaluated the ability of APSIM to predict the response of maize to manure inputs as observed in on-farm experiments in Murewa (higher rainfall) and Tsholotsho (lower rainfall) communal areas of Zimbabwe. Three experiments were used in the study. The first experiment studied the initial and residual effects of pit and heap-stored manure on maize grain yields. The 3-year experiment was conducted on a granitic sand in Murewa, with a single application of manure in the first cropping season. APSIM failed to simulate the contrasting initial and residual yield trends observed for pitted and heaped manure. However, chemical characterisation of heaped and pitted manure was contrary to observed behaviour, and the residual effects of the manures may have been masked by the application of inorganic N. The second experiment, also in Murewa, examined combinations of manure with high N concentration and N fertiliser. The model successfully predicted maize grain yield response to the combinations and manure alone, but greatly over-predicted the yield for fertiliser alone. The third experiment examined maize biomass yield response to heap- and pit-stored manure in the drier Tsholotsho region, across several farms on sandy and clay soils. The model successfully predicted mean biomass yield trends for the sandy and clay soils, and higher yields on the clay than the sand. Simulation of the effects of increasing amounts of pit and heap manure (from 0 to 15 t ha^{-1}) was largely in agreement with the observed responses. Results of this study demonstrate the need for improved experimentation and measurements of manure quality in order to better understand crop response to applications of pit and heaped manure. This will provide, in turn, a sounder basis for further testing of the model's ability to predict the effectiveness of poor-quality manures.

Manure is used as the main source of nutrients for crop production in most communal areas of Zimbabwe (Mugwira and Mukurumbira 1984; Mugwira and Murwira 1997). This is more so in high rainfall areas, where crop response is more certain, than in drier areas, where manure resources are often underutilised (Ahmed et al. 1997). However, manure from communal grazing areas is nearly always of low quality (N < 1%) (Tanner and Mugwira 1984) and its low N content in particular is attributed to poor feed quality and losses during handling and storage (Probert et al. 1995).

Nzuma and Murwira (2000a) conducted a study to reduce N losses from manure through improved handling and storage practices. They compared the use of manure from the conventional heap-storage systems to pit-stored manure. The pit storage

* TSBF–CIAT, Box MP 228, Mt Pleasant, Harare, Zimbabwe <tsbfzim@zambezi.net>.
† ICRISAT, Box 776, Bulawayo, Zimbabwe <j.dimes@cgiar.org>.
§ ICRAF-Zimbabwe Agroforestry Project, c/o AREX, Box CY594, Causeway, Harare, Zimbabwe <nnsprl@mweb.co.zw>.
¶ Tobacco Research Board, Kutsaga Research Station, Box 1909, Harare, Zimbabwe.

systems reduced N losses, as was indicated by high total N and ammonium N concentrations in the pitted manure compared with heap-stored manure (Nzuma and Murwira 2000b). When applied to maize in a high-rainfall region, the pit-stored manure gave higher grain yields than heap-stored manure (Murwira 2003). The efficacy of high-quality manures has been further evaluated in field experiments that combined manure and inorganic N application and varied soil type and rates of application in semi-arid regions of Zimbabwe (Murwira et al. 2001).

Biophysical simulation models such as APSIM (McCown et al. 1996; Keating et al. 2003) and CERES–Maize (Jones and Kiniry 1986) have been used to predict crop response to inputs of inorganic N under African conditions. For example, Shamudzarira and Robertson (2002) used APSIM to simulate responses of maize to N fertiliser, and compared the output with observed data from a long-term experiment conducted at Makoholi Research Station in central Zimbabwe. Their results showed that the model predicted grain yield responses to a range of N rates (0, 20, 40, 80 kg N ha^{-1}) within one standard error of the observed in nearly all seasons. Importantly, the model was able to simulate the very low biomass and zero grain yield observed in the 1991–92 drought season (simulated biomass = 500 kg ha^{-1}, observed = 580 kg ha^{-1}). Such low yield levels are characteristic to most African farming systems, particularly in the semi-arid regions. With the addition of the APSIM–Manure module (Probert and Dimes 2004), APSIM acquired the capability to predict nutrient availability following the addition of organic as well as inorganic sources of N in smallholder farming systems. While this capability has been shown to assist in exploring various management options under African conditions (Carberry et al. 2002), there has been no evaluation of APSIM to simulate observed crop response to manure applications in the field.

In the study reported here, a series of manure experiments conducted in wet and dry regions of Zimbabwe was used to evaluate APSIM for simulating maize response to applications of manure with varying N content and availability. The intention was to better understand where APSIM–Manure could be usefully applied and to identify possible areas for improvement in the model.

Materials and Methods

Three experiments were used to evaluate APSIM's performance to predict maize response following applications of different quality manures. The first experiment studied the initial and residual effects of pit- and heap-stored manure on maize yield in a high rainfall region. It was conducted on a coarse grained, shallow granitic sand soil in Murewa, Zimbabwe.

Manure was taken from open kraals in July 1997 and stored as follows:

Heap – straw:	manure stored in uncovered heap without straw
Heap + straw:	manure plus added maize stover stored in uncovered heap
Pit – straw:	manure stored in a covered pit without straw
Pit + straw:	manure plus added maize stover stored in a covered pit

Manure from the different storage systems was removed in October 1997 and incorporated into field plots on an equal total N basis (60 kg N ha^{-1}) before sowing the first maize crop. Residual effects of the manure applications were evaluated in cropping seasons 1998–99 and 1999–2000. Basal P fertiliser was applied to all the treatments, including a control plot that had no manure. N fertiliser was applied to all plots that received manure, but not to the control, in two applications (20 + 20 kg N ha^{-1} as ammonium nitrate, in all three cropping seasons. Medium duration maize (SC501) was grown as the test crop. There were three replications for treatment plots.

For the second experiment, manure from a commercial feedlot (%N = 2.7, %C = 19.2) was used to determine the effects of organic–mineral fertiliser combinations on maize yields in Murewa in 1997–98. Manure and ammonium nitrate (AN) were applied at a total N rate of 100 kg N ha^{-1}. All the manure was applied at planting, while fertiliser N was applied as split dressings at 4 and 8 weeks after crop emergence. The following combinations were tested:

1. Control (no N applied)
2. 100% AN : 0% manure
3. 75% AN : 25% manure
4. 50% AN : 50% manure
5. 25% AN : 75% manure
6. 0% AN : 100% manure

The third set of experiments was carried out in a semi-arid environment near Tsholotsho, Zimbabwe, during the 2000–2001 cropping season. Farmer-managed manure (pit-stored and heaped-manure) was applied on clay (7 farms) and sandy (6 farms) soils at the rate of 3 t ha^{-1}, with three replicates at each farm. The effects of rate of manure application (0, 3, 6, 9, 12 and 15 t ha^{-1}) were also studied on one farm (sandy soil) with three replications. A short season maize variety (SC401) was used in Tsholotsho.

Simulations

To simulate experiments 1 and 2, daily temperature and radiation data from a nearby weather station (in Natural Region II which receives an annual rainfall of 800–1000mm; Vincent and Thomas 1961) were used in conjunction with daily rainfall measured at the site. Soil parameters for describing N and organic C content of soils were measured, while the soil water balance was estimated based on knowledge of the soil (N. Nhamo, unpublished data). Plant available water capacity (PAWC) to rooting depth (90 cm) was 73 mm, and percentage C in the surface layer was 0.7. For experiment 1, the amount of manure added to the soil varied between treatments according to the N contents (Table 1) to apply 60 kg N ha^{-1}. Initial soil water for simulations was assumed to be close to the lower limit (LL) of plant available water capacity and soil mineral N was set to approximately 10 kg N ha^{-1}. Experiment 1 was simulated without any re-sets for soil water and N in the residual seasons.

For Tsholotsho experiments, temperature and radiation data from a station representative of Natural Region IV was used in conjunction with rainfall data measured at the site. The soil descriptions used for simulating these experiments were:

clay soil — 1.05 m deep, PAWC of 100 mm and 1.4% C in the surface layer:

sandy soil — 1.0 m deep, PAWC of 57 mm and 0.4% C.

Initial mineral N for each soil (i.e. a sand and a clay) was chosen so that the simulated biomass yields for the control treatment was similar to the average of measured farmer yields on each soil type. The chemical data available for the manures from Tsholotsho farms (6 heap and 3 pit) show little difference in C and N content of heaped and pit-stored manure (data not shown); this contrasts with manures at Murewa (Table 1). Hence, the manure treatments in Tsholotsho were simulated using the same % C (10%) and only a small difference in N content (heaped 0.6% and pit-stored 0.75%).

For this study, the partitioning of manure carbon into the three pools comprising fresh organic matter (Probert and Dimes 2004) was in the ratio 0.3:0.3:0.4 for the pit-stored manure and 0.01:0.59:0.4 for heaped manure. These values imply that there is material in the pit-stored manure that decomposes and releases N more rapidly than the heaped manure.

Results

Manure storage experiment at Murewa

Manure characterisation

Table 1 shows the chemical characterisation for manures used in Experiment 1 at Murewa. Pit-stored manure had higher carbon, total N and cation concentrations and lower ash content than heaped manure. Despite its higher N concentration, the pit-stored manure had a higher C:N ratio, though all manures had C:N ratios considered conducive to net mineralisation of N (i.e. < 20). Addition of straw during storage had smaller effects on composition than the effect of method of storage.

Initial and residual maize responses

Rainfall in each of the three cropping seasons exceeded 1000 mm. In the first cropping season, pit-stored manure gave much higher grain yields than the control or heaped manure treatments (Figure 1a). In subsequent seasons, maize yields for this treat-

Table 1. Characterisation of manures from manure storage experiments in Murewa.

Treatment	C %	N %	P %	K %	Ca %	Mg %	Ash %	C:N ratio
Heap – straw	9.0	0.88	0.20	0.25	0.21	0.53	80.9	10.2
Heap + straw	11.9	0.96	0.13	0.26	0.11	0.21	76.5	12.3
Pit – straw	28.2	1.84	0.25	0.84	0.25	0.70	40.7	15.3
Pit + straw	30.0	1.54	0.28	0.76	0.26	0.57	55.6	19.5

ment declined. In contrast, heaped manure had low yields in the first season, and an increasing yield trend for the second and third seasons, to the extent that yields exceeded those for the pit treatment in the residual seasons. Cumulative yield for the three seasons was higher for pitted manure (7 t ha^{-1}) than for heaped (5.4 t ha^{-1}), and both were greater than for the control treatment, which produced 2.2 t ha^{-1} for the 3 years.

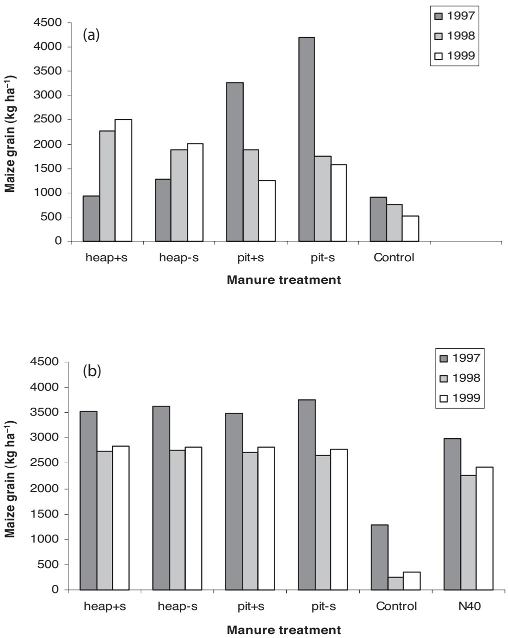

Figure 1. Initial and residual effects of heap- and pit-stored manure, with (+s) and without (–s) straw additions on maize grain yields at Musegedi farm in Murewa, Zimbabwe. a) Observed field responses; b) simulated responses.

The simulated yields for the control treatment that received no inputs of N were small in all three years and agreed reasonably well with the observed data (Figure 1b). However, the simulated responses to heaped and pitted manures were almost identical. Clearly, the model failed to simulate the contrasting release patterns observed for the pit-stored and heaped manure in the field. To explore the discrepancy, we tested the prediction for a treatment that received 40 kg N ha^{-1} as fertiliser but no manure (included in Figure 1b); it was predicted to yield higher than any of the observed manure treatments except pit-stored manure in the first season. The model predicted that the yields with both manure and fertiliser would be slightly higher than for fertiliser alone.

Manure–fertiliser N combinations at Murewa

Grain yield response to various combinations of manure and fertiliser applying a total 100 kg N ha^{-1} to maize at Murewa are shown in Figure 2. Combinations gave higher maize yields than sole fertiliser or sole manure. The 100% manure and 100% fertiliser treatments gave almost identical maize yields, and these were more than double the yield of the control treatment that received no inputs of N.

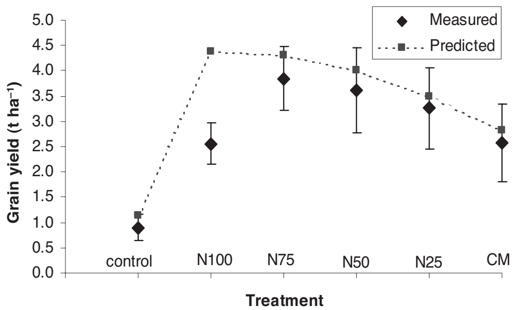

Figure 2. Measured and predicted effects of 100 kg N ha^{-1} applied as combinations of manure and fertiliser N on maize grain yield at Murewa in the 1997–1998 cropping season. (Control = no N inputs, N100 = 100 kg N ha^{-1} applied as fertiliser, CM = 100 kg N ha^{-1} applied as manure). Error bars denote standard deviations of measured means.

The model predictions agreed closely with the observed yields for the control and in response to the manure and fertiliser inputs, except for the 100% fertiliser treatment, for which there was a large over-prediction. The trend for yields to increase as the proportion of the N applied as fertiliser increased shows that the high-quality manure used in this experiment was a relatively less effective source of N than the fertiliser.

The reason for the poor prediction of the 100% fertiliser treatment is not known. One explanation could be that the manure inputs supplied some other limiting resource such as another nutrient (e.g. Ca, Mg, S or Zn) or had a liming effect. Such benefits of manure are not considered in the model.

Manure experiments at Tsholotsho

As a consequence of low rainfall, larger differences in maize growth were observed between soil type than between pit-stored and heap-stored manure in the Tsholotsho experiments. On both the clay and sandy soils, maize biomass was higher with manure inputs relative to the control, with pit-stored manure having the highest biomass yields overall, but these differences were although not statistically significant (Figure 3).

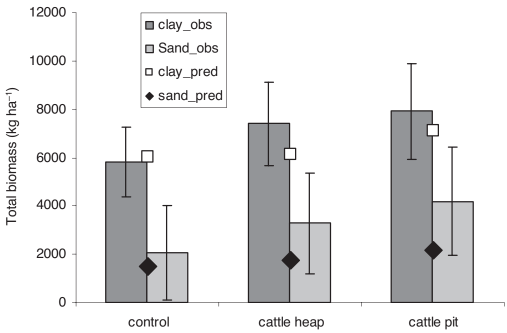

Figure 3. Observed and predicted maize response to heaped and pit-stored manure on clay (mean of 7 farms) and sandy (mean of 6 farms) soils near Tsholotsho in cropping season 2000–2001. Error bars denote standard deviations of measured means.

The model successfully predicted maize biomass yields within one standard deviation of the measured yields for the sandy and clay soils (Figure 3). The model also predicted a trend in maize biomass yields for the two soils, with the control treatment having the lowest maize yields and the pit manure treatment the highest.

For the experiment testing rates of manure on a sandy soil, highly variable maize responses were observed in the field (Figure 4). The model could predict the main trends, with maize yield increasing with increasing rates of application, and pit-stored manure having a higher yield trend than the heaped-manure. However, in this experiment, it should be noted that manure was applied on an equal mass basis, rather than equal N. Hence, differences in maize response between the two manure sources are exaggerated by the respective amounts of N added.

Discussion

The simulations did not always agree with the observed data. Unfortunately, reasons for the lack of conformity are not straightforward. Here we discuss matters that emerged in the testing of the model.

At the wetter location, the observed yields showed a larger response in the first season to the pit-stored manure than to heaped manure (Figure 1). While the pit-stored manure had higher N concentration, this should have been accounted for in the experimental

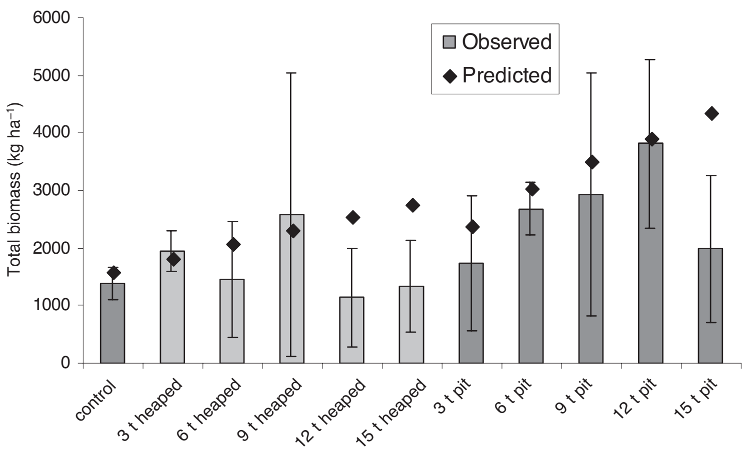

Figure 4. Observed and predicted effects of application rate (t ha^{-1}) of heaped and pitted manure on maize yields in Tsholotsho, in 2000–2001 cropping season. Error bars denote standard deviations of measured means.

design in that the manures were compared on an equal N basis. The expectation is that manure quality depends primarily on its C:N ratio and it is such concepts that are built into the model. In terms of C:N ratio, the pit-stored manures had higher values than the heap-stored manure so it would be expected to be a poorer source of N to the first crop. The model accurately predicted the low yields for the control treatment. The fertiliser N that was applied along with the manure treatments effectively masked any differences in the predicted yields for these treatments. It is unclear why the measured yields from the heaped manure should be so low. In the year of application there wasn't enough carbon added (680 kg C ha^{-1}) in the applied manure to immobilise the 40 kg N added as fertiliser. In the residual years, there is even less reason to expect the manure treatments to reduce the effect of the fertiliser input.

The simulations of the treatments of experiment 2 involving higher quality manure from a commercial feedlot were satisfactory, except for the treatment where fertiliser was the sole source of N. This treatment was seriously over-predicted. Above it was suggested that manure might have provided some benefit that is not considered by the model. Alternatively, one needs to invoke some mechanism that would result in reduced response to the 100% fertiliser treatment, though how this could be without similarly affecting the 75% fertiliser treatment is somewhat implausible.

The responses measured in experiment 3, particularly to the heap-stored manures, were small and variable (not statistically significant) (Figures 3 and 4). Thus, they are not well suited to providing insights into shortcomings of the model.

The attempts to model these experiments have highlighted several difficulties. The most obvious is that, where there is poor understanding of the measured responses, there can be little basis for judgment on the performance of the model. There is clearly scope for improving the design of experiments to test efficacy of manures (e.g. by not confounding the effects of manure and fertiliser); there is need to identify other possible benefits of manures besides N supply to crops; testing the performance of models would be aided if fuller information were available on initial soil conditions (soil water, mineral N) and it was possible to compare components of crop growth other than grain yield (e.g. total biomass and N uptake).

The results from experiment 1 show our inability to link the analyses of manures that are customarily made (e.g. Table 1) with their observed behaviour in the field. As a result of this study, new experimentation has begun in which the mass balances of C and N will be monitored during storage of manures in the dry (P. Masikate, unpublished data) and wet regions (P. Chivenge, unpublished data).

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