Modelling minimum residue thresholds for soil conservation benefits in tropical, semi-arid cropping systems

M.E. Probert

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Cover: A women's farmer group, participating in on-farm trials into the effects of partial retention of maize residues on long-term crop production, near Polokwane, Limpopo province, South Africa. Photo: C. Roth.

Foreword

Developing and promoting farming systems that make use of conservation tillage practices (minimum tillage, zero tillage) in combination with the retention of crop residues is a strategy being pursued by many national and international research organisations. It is also a research topic that has been supported by the Australian Centre for International Agricultural Research (ACIAR), through a range of projects in China and India. The potential benefits of conservation agriculture are significant but, in many instances, they are not being realised. One of the many reasons for this is that competition from use of crop residues for fuel and forage is impeding adoption of residue retention, a practice that is recognised as a critical element in regenerating degraded soils or enhancing productivity of more intensively cropped soils.

There are no long-term experimental data from semi-arid tropical countries of Asia and Africa on the benefits of residue retention. The targeted modelling study described in this report was implemented to explore in a preliminary way the extent to which partial retention of residues might provide a way forward. Farmers may find partial retention an acceptable compromise, enabling them to maintain some use of residues for livestock and divert the balance to soil fertility management and erosion control. The results of the study will contribute to the debate on the potential and limitations of the conservation agriculture concept in semi-arid tropical environments, particularly in drier, lower productivity areas. They should also help ACIAR and other funding organisations to improve decision-making about investing in research and development projects aiming to introduce conservation agriculture into the poorer regions of Asia and Africa.

Peter Core.

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Director, Australian Centre for International Agricultural Research

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Acronyms and abbreviations

ACIAR	Australian Centre for International Agricultural Research
APSIM	Agricultural Production Systems Simulator
PAWC	plant available water content to crop rooting depth
SMI	soil moisture index
SOC	soil organic carbon

APSIM parameters

DUL	volumetric water content at drained upper limit
LL	volumetric water content at lower limit of extraction of water by crop
SAT	volumetric water content at saturation
cn2	curve number of soil that determines run-off

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Summary

In this study, a modelling approach was taken to investigate the benefits of conservation agriculture in the semi-arid tropics. The model used was the Agricultural Production Systems Simulator (APSIM) release version 4.1.

Four case studies were modelled: two were maize-cropping systems on sandy soils in southern Africa; two were maize and wheat-cropping systems on a Vertosol (clay soil) in south-eastern Queensland, Australia. In each case, there was a combination of scenarios, with five levels of residue retention (0, 25, 50, 75 and 100%) and four levels of fertility involving fertiliser inputs and initial soil organic carbon (SOC) content. The following outputs from the model are presented: crop production (grain and stover), components of the water balance, and changes in SOC.

Results are summarised as the long-term averages of crop yields and water balance components. However, it is shown that this approach masks the complexity of the response to residue management. Season-to-season variation is marked, and responses in crop growth can be either positive or negative.

The following conclusions are derived from the simulations.

The effects of retention of maize or wheat residues on average long-term crop production were modest. The largest effects were found for the maize system at Dalby, Queensland. Judged in terms of excess water (the sum of run-off and drainage) this was the driest site.

The simulations show that residue management does have implications for SOC. The trends in SOC could be related to residue management to determine thresholds of residue retention that resulted in no change in SOC content. For soils with low initial SOC, these thresholds were approximately 60% residue retention for adequately fertilised crops; for nitrogen-limited crops, even 100% residue retention failed to maintain SOC (except at the Makoholi location, which had the lowest SOC content). Where initial SOC was 50% higher, approximately 100% retention of residues was the threshold for the Makoholi location, but there were inadequate residues to maintain these higher SOC contents for the other case studies.

For crop yields and components of the water balance, the notion of threshold levels of residue retention (or of residues) that determine whether beneficial effects are obtained from conservation agriculture was less helpful. Variation in rainfall, and carryover effects of water and/or nitrogen, complicate the interpretation of responses. Crop yield response to residue retention can change from positive to negative. Positive effects will occur where residues reduce run-off and/or evaporation so that the crop experiences an improved water supply (generally in years of low rainfall), provided that the nutritional status is adequate.

The results from the simulations highlight that the response of such systems is complex and show why these systems are not well suited to experimentation. It seems unlikely that carrying out ‘simple’ experiments investigating conservation cropping will lead to clear answers about the benefits of retaining crop residues.

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Introduction

Conservation agriculture strives to increase yields, gain efficiencies in input use and maintain the long-term productivity of land and water resources, in turn contributing to increased profitability and sustainability of farming enterprises. The crop residues produced in the system are kept on the soil surface rather than incorporated, and serve as a physical protection of the soil and a substrate for the soil fauna. In this way, soil organic matter is built up and maintained. However, the practicality of the fundamental premise of conservation agriculture of retaining all residues is being increasingly questioned, especially in the case of drier climates. A large proportion of the marginal dryland farming regions in the semi-arid tropics is characterised by mixed livestock–cropping systems, in which competition for forages and fodder invariably results in low levels of residue retention, even in conservation-tillage-based systems. In reality, given a choice, farmers in these systems will opt to invest in their animals rather than their soils, as the opportunity costs for residue retention in most cases tend to be higher than using the residues to feed livestock. Conversely, if it were possible to determine minimum residue retention thresholds for given rainfall, soil and cropping conditions that do lead to gradual improvements in soil fertility and water status, as well as crop productivity, it may be possible to convince farmers to retain a portion of their residues, enabling long-term improvement to soil fertility and water status.

In the past, ACIAR has invested considerable research funds in developing and implementing conservation-tillage-based systems in the semi-arid tropics. Results have been mixed, however, precisely because farmers usually like the cost-saving aspects of zero-till, but generally do not implement residue retention, defeating the primary purpose of conservation tillage. This raises the question of whether ACIAR should continue to invest in such projects.

Resolving this question is significantly hampered by the lack of experimental data showing long-term benefits of residue retention in mixed livestock–cropping systems in the semi-arid tropics. To collect such data would be costly and require considerable time. However, cropping-system models are sufficiently refined to provide an alternative to experimentation. In this study, a modelling approach was taken with the aim of providing a rational basis for future research and development investment decisions in relation to research projects targeted at introducing the conservation-agriculture concept into the semi-arid tropics. The specific aims of the study were:

- to conduct scenario analysis using the Agricultural Production Systems Simulator (APSIM) model to investigate a range of soil, climatic and residue retention levels under zero-till management to obtain relationships between residue rates and soil organic carbon (SOC), soil water balance components and crop yields
- to use the scenario outputs to derive minimum residue thresholds necessary to improve SOC and increase water availability.

Extensive testing and validation of the model used was beyond the scope of this study, as was the broadening of the scenario analysis to include different cropping systems and crop rotations. Rather, the main purpose was to obtain some indicative results that would continue to stimulate the debate about the feasibility of conservation agriculture in the semi-arid tropics, as well as provide directions for future research and funding.

The case studies

The project was carried out as four case studies. The first three were based on maize-cropping systems; the fourth investigated the effect of a winter crop (wheat) at one of the locations, and thus provided an interesting contrast in terms of seasonality of rainfall and soil cover provided by crop residues.

For each case study, simulations were carried out to investigate a combination of: (1) soil fertility levels, and (2) varying crop residue management.

The five levels of crop residue management were 0, 25, 50, 75 and 100% of residues from the previous crop retained on the soil surface.

The soil fertility levels involved both the initial SOC content of the soils and input of nitrogen fertiliser. Levels 1, 2 and 3 were based on the standard soils for the various locations, all of which had low initial SOC (as exist under typical farming practices); level 4 investigated hypothetical soils in which the initial SOC in the 0–20 cm layers was increased by 50% compared with the standard soil, but with the same amount of inert carbon (see Appendix). Table 1 outlines the fertiliser inputs.

Case study 1—referred to as Dan

This was based on the maize-farming system at Dan, Limpopo Province, Republic of South Africa, which has been modelled previously by Whitbread and Ayisi (2004). Details of the soil properties are set out in the Appendix, and soil-water characteristics are displayed as Figure 1. The plant available water capacity (PAWC) of the sandy soil to the rooting depth of maize was 93 mm.

The weather file was for Letaba for 1975–2005. The mean annual rainfall is 774 mm, with 618 mm in November–March. Table 2 provides further details of rainfall variability. Thirty seasons were simulated, commencing in April 1975.

The maize cultivar was the short-season variety SC401, which was sown every year using a rainfall-based sowing rule:

- sowing window: 15 November – 15 January
- sowing criteria: soil moisture index[1] (SMI) (10–20 cm layer) > 0.5 and rainfall of at least 20 mm over 5 days
- plant density: 4 plants/m^2.

Fertiliser inputs were:

- low N: 20 kg/ha as urea
- high N: 100 kg/ha as urea applied as three splits (at sowing and 30 and 60 days after sowing).

Case study 2—referred to as Makoholi

This was based on the maize-farming system at Makoholi, near Masvingo, Zimbabwe, which has been modelled previously by Shamudzarira and Robertson (2002). Details of the soil properties are set out in the Appendix, and soil-water characteristics are shown in Figure 1. The PAWC of the deep sandy soil to the rooting depth of maize was 56 mm.

Table 1. Description of the four fertility levels investigated in each case study

	Soil	Fertiliser inputs
Level 1 (zero N)	Standard	None
Level 2 (low N)	Standard	Single sub-optimal application of nitrogen
Level 3 (high N)	Standard	Near optimal application as split applications of nitrogen
Level 4 (high initial SOC)	High SOC[a]	Same as Level 3

[a] Initial soil organic carbon (SOC) in 0–20 cm layers was increased by 50% compared with standard soil.

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[1] The soil moisture index measures the plant available water as a proportion of the total water-holding capacity for the soil layer.

The weather file was for Makoholi for 1951–2004. The mean annual rainfall is 660 mm, with 517 mm in November–March. Thirty-four seasons were simulated, commencing in April 1969.

The maize cultivar was the variety SC501, which was sown every year using a rainfall-based sowing rule:

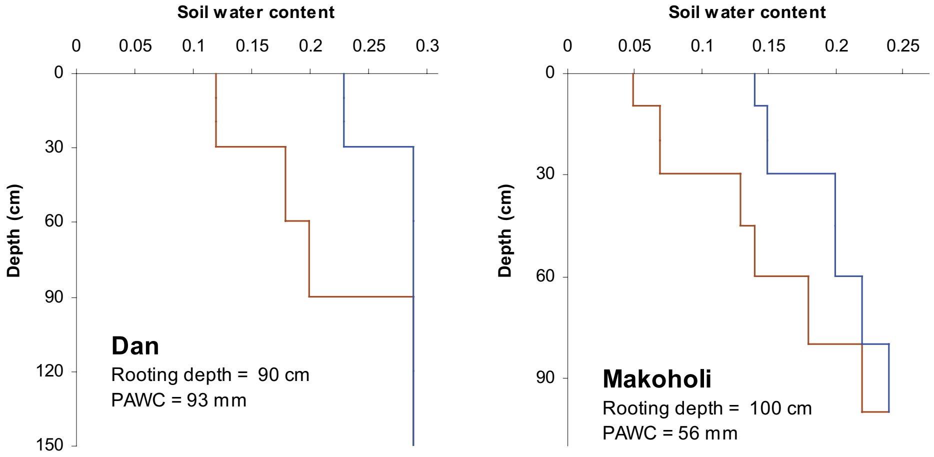
- sowing window: 1 November – 15 January
- sowing criteria: SMI (10–20 cm layer) > 0.5 and rainfall of at least 25 mm over 10 days
- plant density: 3.5 plants/m^2.

Fertiliser inputs were:

- low N: 15 kg/ha as urea
- high N: 45 kg/ha as urea applied as three splits (at sowing and 30 and 60 days after sowing).

Table 2. Rainfall variability at the three locations

Location	Mean annual rainfall (mm)	November–March rainfall		
		Mean (mm)	Range (mm)	CV (%)
Letaba	774	618	237–1459	44
Makoholi	660	517	129–1006	39
Dalby	698	409	236–857	29



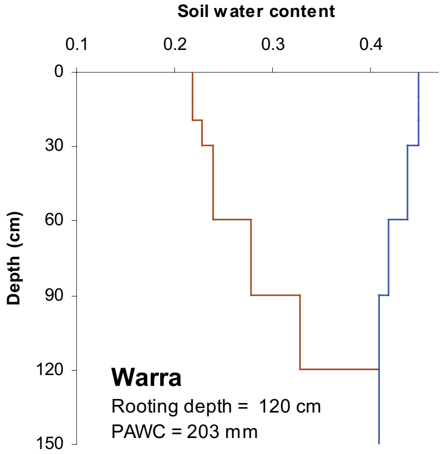


Figure 1. Soil water properties of the three soils used in the case studies. The lines denote the drained upper limit (DUL) and crop lower limit (LL). The plant available water capacity (PAWC) of the three soils is shown.

Case study 3—referred to as Dalby

This was a hypothetical maize-farming system at Dalby, Queensland on a Vertosol. Summer cereals are grown at this location (sorghum more frequently than maize), but not continuous maize as for subsistence cropping in Africa.

The soil properties used were those for the Vertosol at Warra, a self-mulching grey clay with high PAWC, which have been used extensively for modelling farming systems in the region (e.g. Dalal et al. 2004). Details of the soil properties are set out in the Appendix, and soil water characteristics are displayed in Figure 1. The PAWC of the Vertosol to the rooting depth of maize was 203 mm.

The weather file was for Dalby for 1957–2001. The mean annual rainfall is 698 mm, with 409 mm in November–March. Forty-three seasons were simulated, commencing in March 1958.

The maize cultivar was the variety Dekalb XL82, a tropical hybrid with photoperiod sensitivity, which was sown every year using a rainfall-based sowing rule:

- sowing window: 15 September – 10 January
- sowing criteria: SMI (20–30 cm layer) > 0.5 and rainfall of at least 20 mm over 5 days
- plant density: 4.5 plants/m^2.

Fertiliser inputs were:

- low N: 20 kg/ha as urea
- high N: 90 kg/ha as urea applied as three splits (at sowing and 30 and 60 days after sowing).

Case study 4—referred to as Dalby (wheat)

This was a wheat-farming system at Dalby, Queensland on a Vertosol. The same soil and weather files were used as for case study 3 and it was assumed that the PAWC of the Vertosol to the rooting depth of wheat was identical to that for maize.

Forty-four seasons were simulated, commencing in December 1957.

The wheat cultivar was the variety Hartog, which was sown every year using a rainfall-based sowing rule:

- sowing window: 10 May – 20 July
- sowing criteria: plant available water > 100 mm and rainfall of at least 20 mm over 5 days
- plant density: 100 plants/m^2.

Fertiliser inputs were:

- low N: 25 kg/ha as urea
- high N: 75 kg/ha as urea applied as two splits (at sowing and 30 days after sowing).

The model

APSIM is a farming systems modelling tool that can be applied to complex climate–soil–plant–vegetation management systems (McCown et al. 1996; Keating et al. 2003). It is a modular modelling environment, with a communications infrastructure linking various biological, environmental or management modules. Key modules deployed in this study included SOILWAT2, which uses a multi-layer, cascading approach for the water balance with run-off estimated using the United States Department of Agriculture run-off curve number (Probert et al. 1998); SOILN2 for soil carbon and nitrogen transformations; SURFACEOM for surface residue dynamics and interactions with soil water and C/N processes; MANAGER for conditional control of the farming system management; and the plant modules MAIZE and PLANT configured for wheat.

The release code used was APSIM v 4.1.

Further detail on the APSIM modules and reports of model performance in a diverse range of studies can be found at <www.apsim.info>.

Model parameterisation

The weather and soil parameter files used in this study had all been used previously for simulations of cropping systems at the various locations. The only changes made were adjustments to depth of soil layers, in order to output SOC contents of the 0–10 and 10–20 cm layers. The soil properties for the three soils are summarised in the Appendix.

The soil water balance (as represented by the SOILWAT2 module) is described in terms of volumetric water content at saturation (SAT), drained upper limit (DUL) and the lower limit of extraction of water by the crop (LL). Different crops may not extract water to the same extent. The ‘15-bar water content’ (LL15) is usually estimated from the driest observed water content (preferably for a deep-rooted perennial crop such as lucerne); biological activity causing mineralisation of soil organic matter is assumed to cease when the soil water content is at LL15. The cascading of water between layers is determined by ‘swcon’, being the portion of water above DUL that moves within the daily time step.

The partitioning of rainfall between infiltration and run-off is determined primarily by the curve number. The bare soil curve numbers (cn2-bare) used for the soils are listed in the Appendix. In the SOILWAT2 module, the effective curve number is a function of the bare soil value and residue cover so that run-off is reduced with increased amount of residue.

The simulations were set up to simulate zero-till management. Crops were harvested once they reached maturity. Following harvest, the MANAGER module permits nominated proportions of crop residues to be removed with the retained residues remaining on the soil surface.

Model initialisation

All scenarios for a given case study were initialised with the same starting conditions. Starting dates, soil water and mineral nitrogen were derived from preliminary simulations for maize (wheat) crops grown with low inputs of N.

Each scenario was simulated as a single run with no resetting of the soil properties.

Outputs

The key outputs presented in the results are:

- crop yields (grain and stover)
- components of the soil water balance (drainage, run-off, evaporation and transpiration)
- SOC in the 0–20 cm soil layer.

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Results

Long-term trends

The overall effects of residue management are summarised in Figures 2–13. For each case study, the figures show:

- effects on average crop yields of grain and stover (Figures 2–5)
- effects on average annual run-off, drainage, evaporation and transpiration (Figures 6–9)
- effects on changes in SOC in the 0–20 cm layer of soil (Figures 10–13).

In general terms, the results for all case studies are rather similar. Retaining increasing proportions of residues has the expected effects of reducing soil evaporation and run-off. However, the long-term average yields show only small effects of residue retention on crop yields overall and, consequently, the transpiration component of the water balance. With no change in transpiration, the reductions in run-off and evaporation must be balanced by increases in drainage.

The crop production is dominated by the effects of the fertility treatments. Yields increase in response to increasing nitrogen (N) inputs, but there is little effect due to the initial SOC content of the soil (showing that the high rate of N was adequate for the crops grown).

The model output shows strong effects of residue retention on SOC. In most instances, the trend is for SOC to decline, particularly where a high proportion of residues is removed, and more so where inputs of N are sub-optimal so that less carbon is available in above-ground residues and roots.

With retention of a high proportion of residues and high inputs of N, it is possible to increase SOC. At Makoholi (Figure 11), for example, with initial SOC of 0.5%, full retention of residues results in SOC increasing for the high N scenario, and declining only slightly for the low N scenario. In contrast, at Dan (Figure 10) with initial SOC of 0.7%, full retention of residues maintains SOC only for the high N scenario, and SOC declines with smaller inputs of N.

Where the soils had high initial SOC it becomes even more difficult to maintain soil carbon through retention of residues.

The two case studies at Dalby compare summer and winter cropping. In the case of maize, the crop is growing so provides cover through the wet season. Wheat, in contrast, is harvested in November or December, so that cover through the wet season can be provided only by crop residues. It was anticipated that this might impact on the effect of residue management. The output shown in Figures 4–5, 8–9 and 12–13 indicates that there were only quite small differences between the two systems. In terms of overall crop production, the effects of residue retention were less for the wheat system than for maize. However, maize cropping with near optimal N inputs does reduce the amount of excess water (run-off plus drainage) compared with wheat cropping.

Confounding effects

The presentation in Figures 2–13 is convenient and appropriate for exploring the gross effects of the various managements. However, such an approach can mask other aspects of the results.

One such effect is that, as SOC declines, it will contribute smaller amounts of mineralised N. Without other inputs of N, this can result in decreasing crop growth. Figure 14 shows such a situation for the Dan case study.

For the scenarios with high N inputs, irrespective of residue management, the crop yields respond to variation in the rainfall. One would not expect there to be a significant trend over time (unless there is a long-term shift in rainfall).

A quite different situation arises, however, for the scenario where zero residues are retained and there are no external inputs of N. Now the declining SOC shown in Figure 10 is accompanied by decreases in crop growth and, by the end of the simulation, grain yields in many seasons are predicted to be zero.

Clearly, the long-term average for this treatment (as shown in Figure 2) includes factors that are absent from some of the other scenarios. Figure 14 indicates that this effect is of greater importance for the scenarios where all residues are removed.

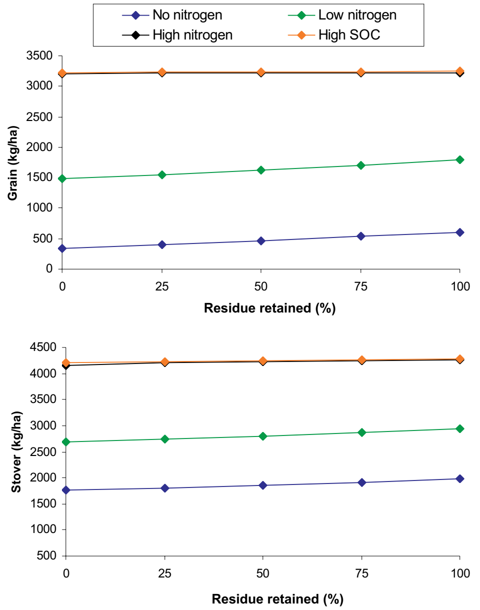


Figure 2. Case study 1—Dan. Effects of residue and soil fertility management (SOC = soil organic carbon) on average crop yields

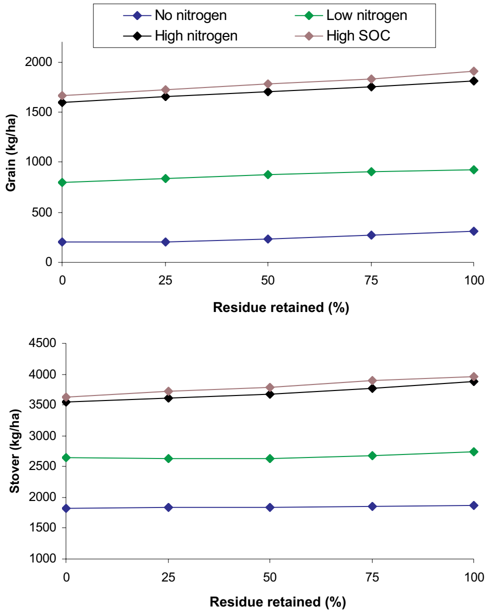


Figure 3. Case study 2—Makoholi. Effects of residue and soil fertility management (SOC = soil organic carbon) on average crop yields

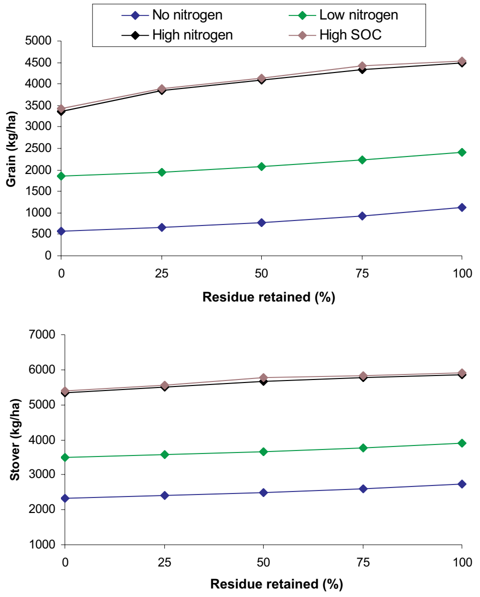


Figure 4. Case study 3—Dalby (maize). Effects of residue and soil fertility management (SOC = soil organic carbon) on average crop yields

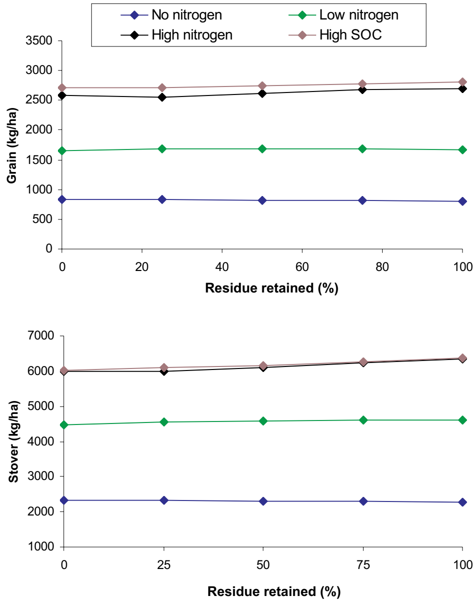


Figure 5. Case study 4—Dalby (wheat). Effects of residue and soil fertility management (SOC = soil organic carbon) on average crop yields

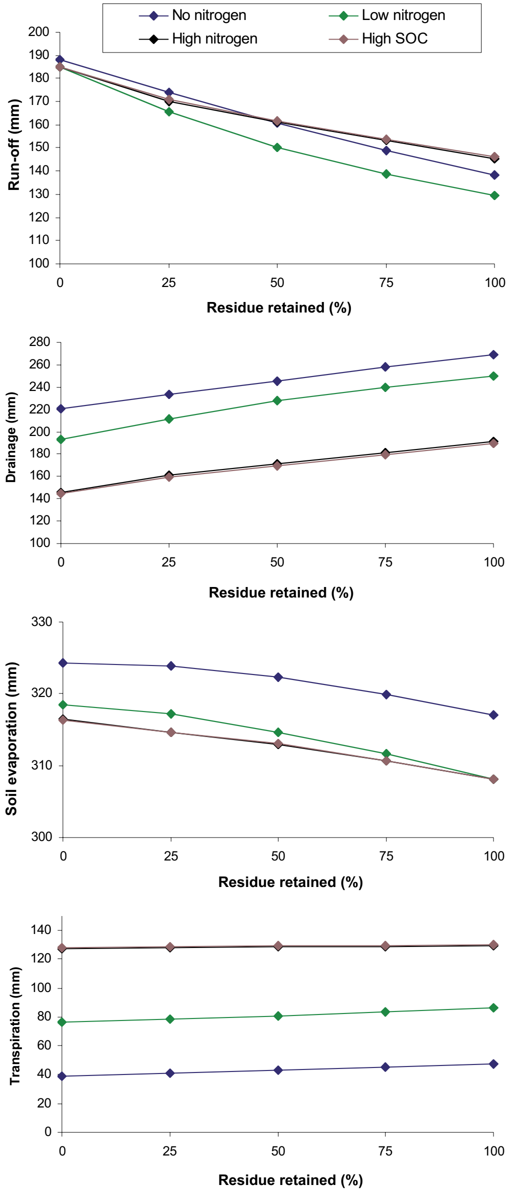


Figure 6. Case study 1—Dan. Effects of residue and soil fertility management (SOC = soil organic carbon) on components of the water balance, expressed as annual means

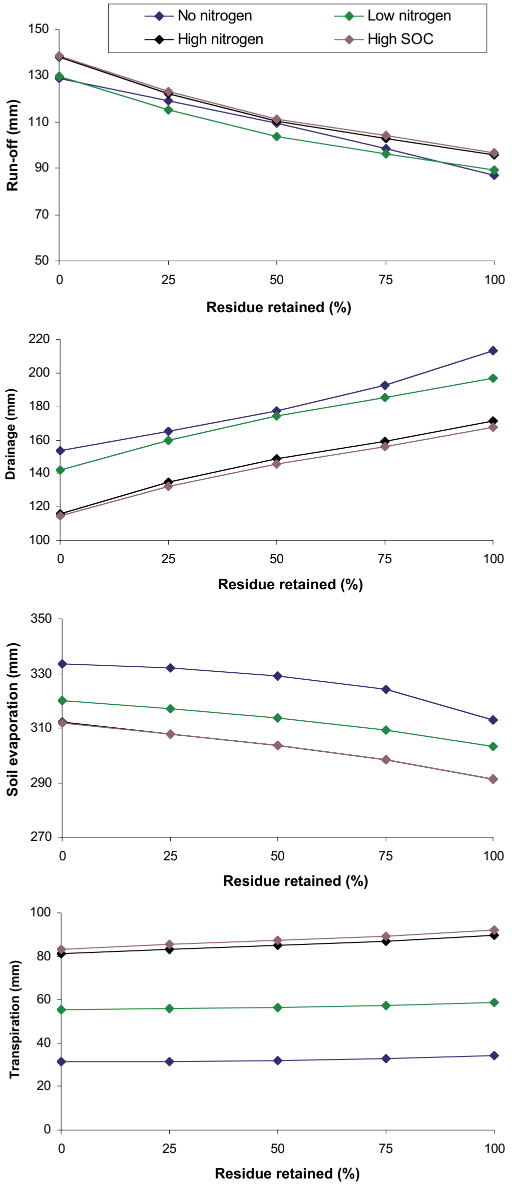


Figure 7. Case study 2—Makoholi. Effects of residue and soil fertility management (SOC = soil organic carbon) on components of the water balance, expressed as annual means

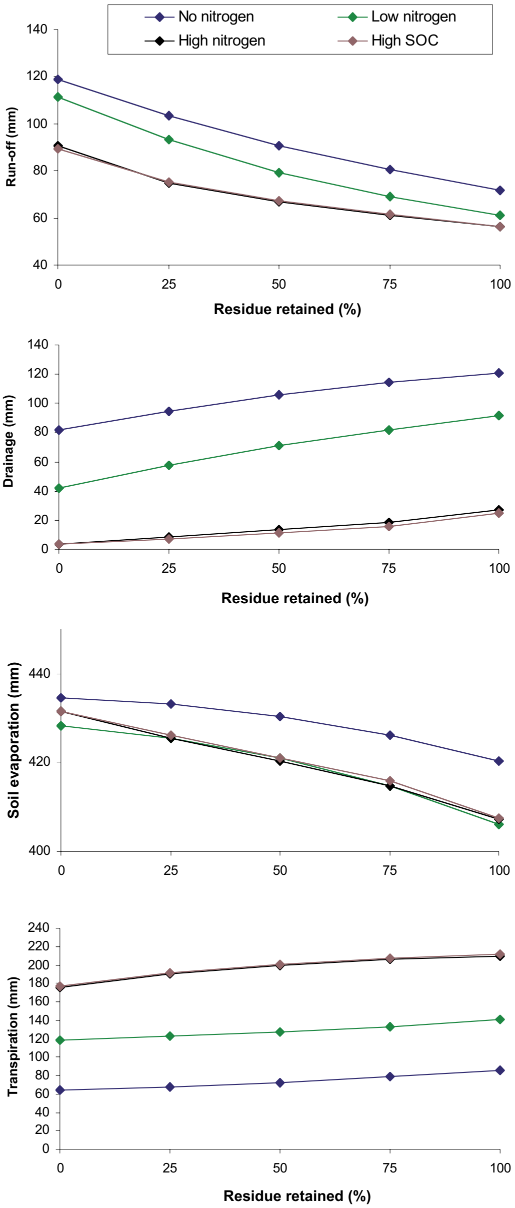


Figure 8. Case study 3—Dalby (maize). Effects of residue and soil fertility management (SOC = soil organic carbon) on components of the water balance, expressed as annual means

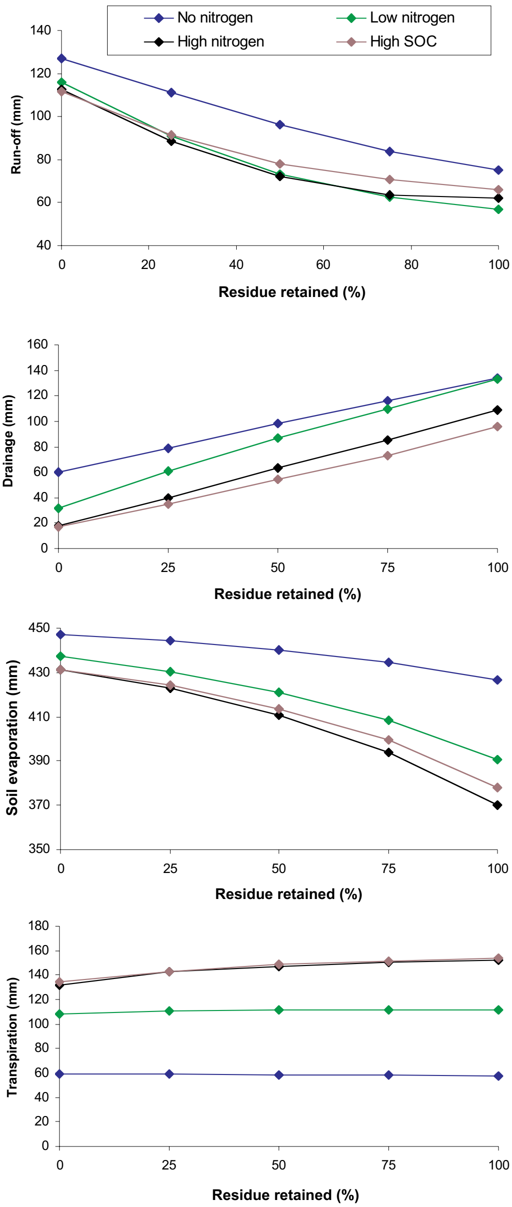


Figure 9. Case study 4—Dalby (wheat). Effects of residue and soil fertility management (SOC = soil organic carbon) on components of the water balance, expressed as annual means

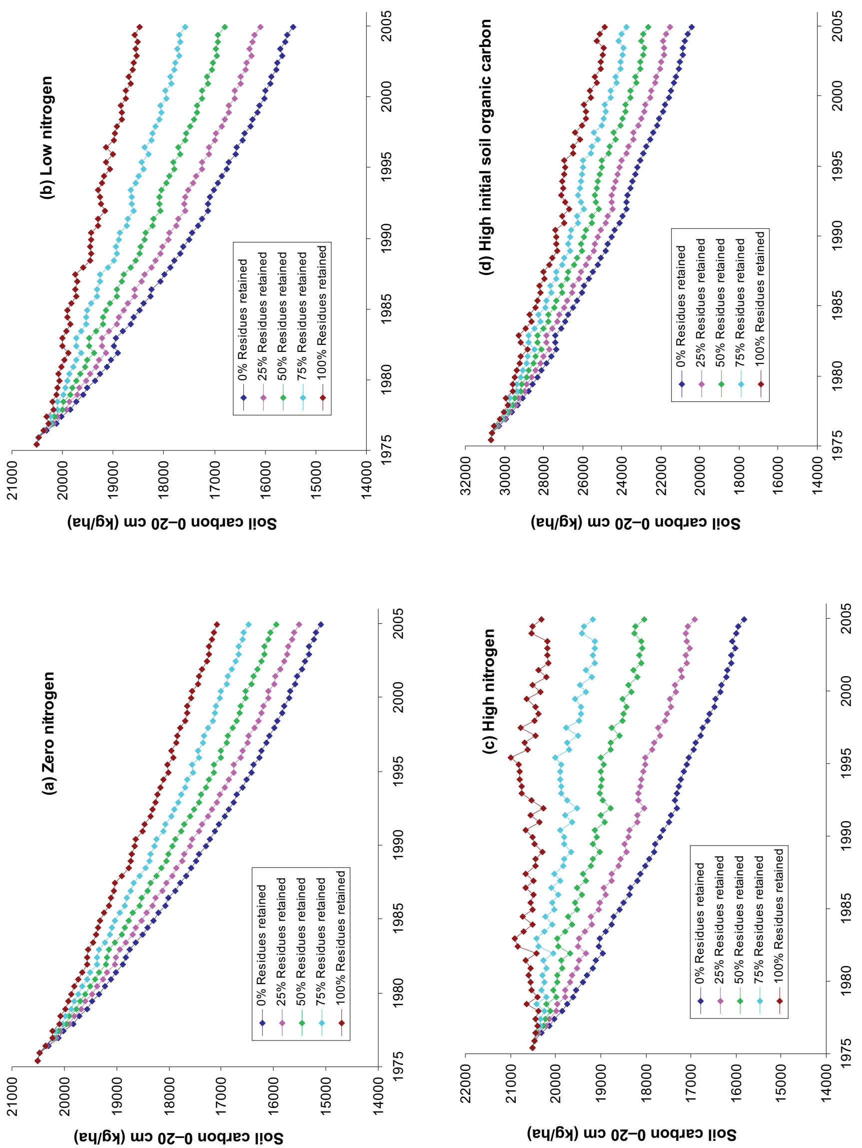


Figure 10. Case study 1—Dan. Effects of residue and soil fertility management on soil organic carbon (SOC) in the 0–20 cm soil

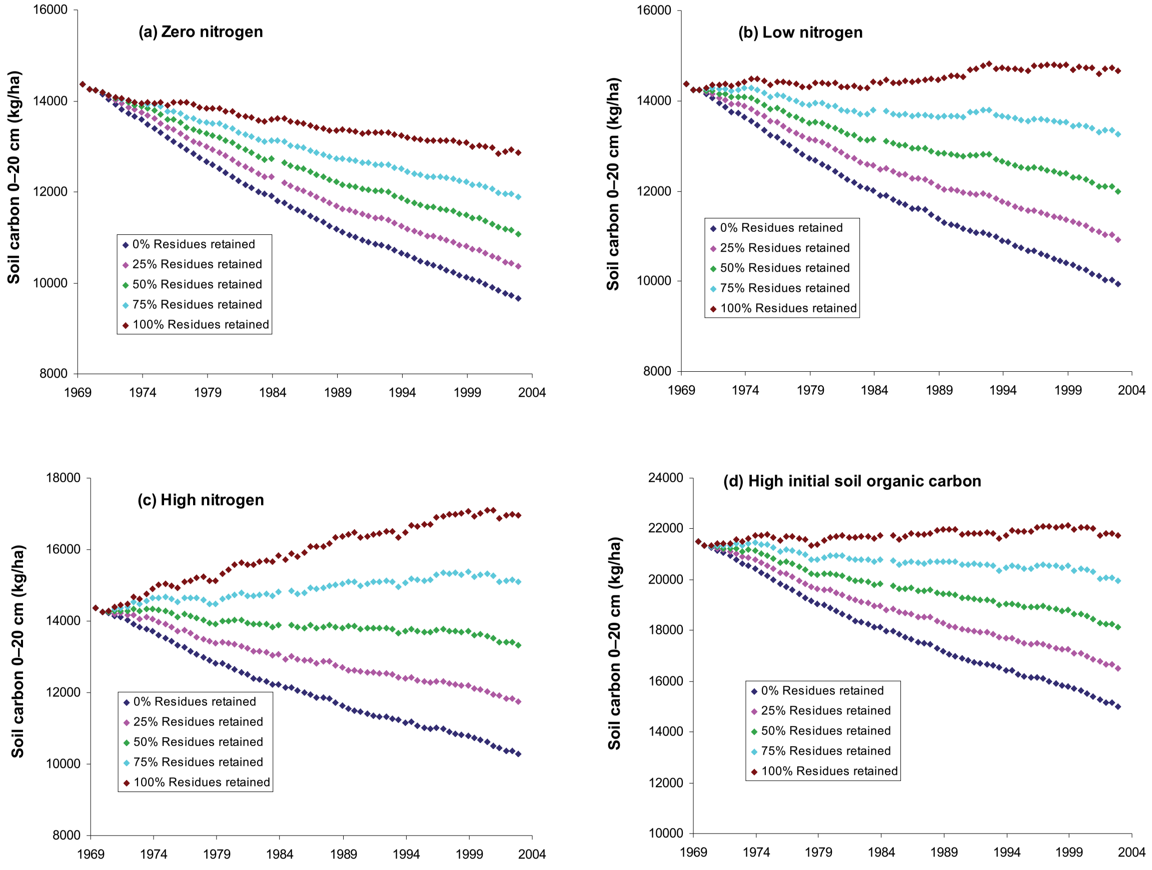


Figure 11. Case study 2—Makoholi. Effects of residue and soil fertility management on soil organic carbon (SOC) in the 0–20 cm soil

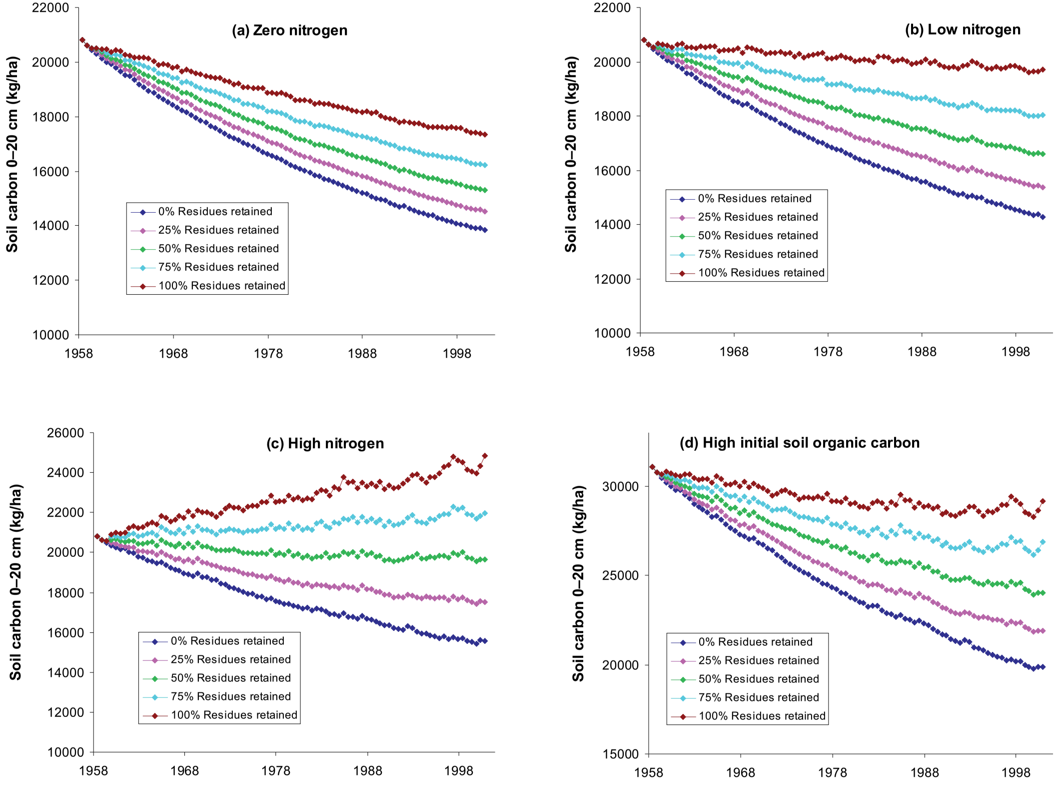


Figure 12. Case study 3—Dalby (maize). Effects of residue and soil fertility management on soil organic carbon (SOC) in the 0–20 cm soil

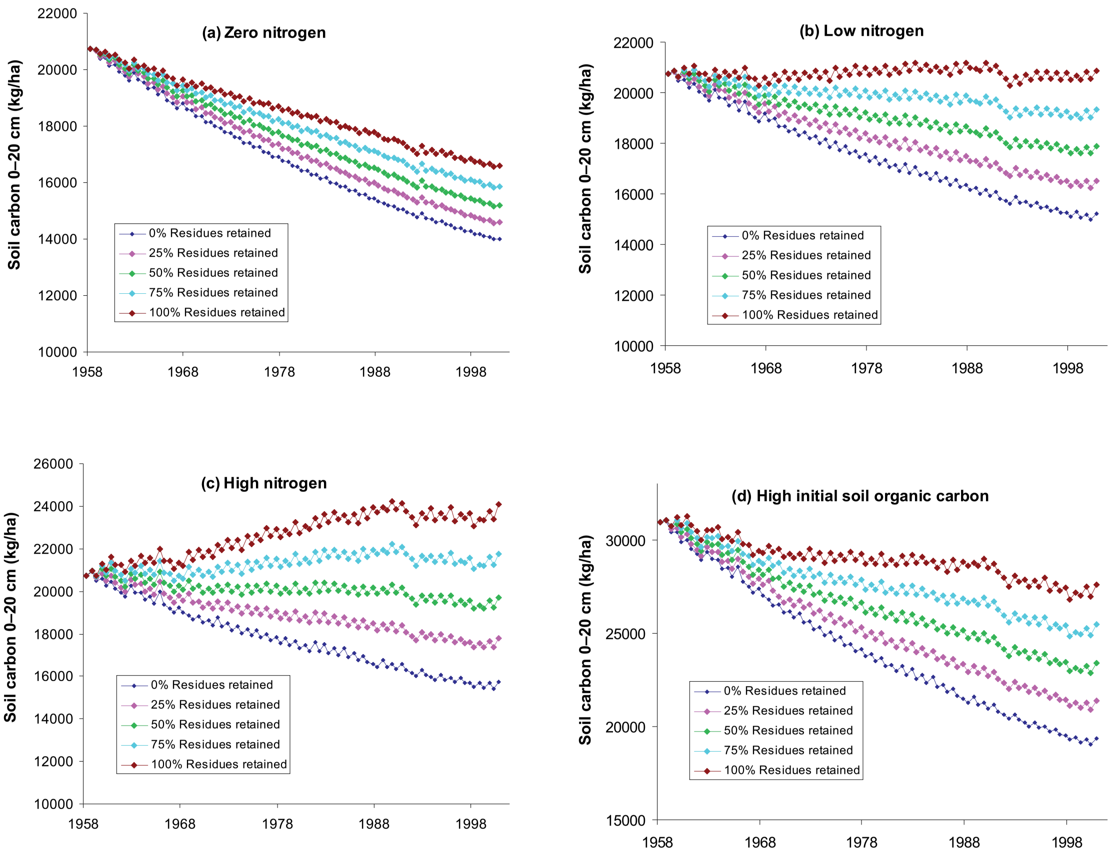


Figure 13. Case study 4—Dalby (wheat). Effects of residue and soil fertility management on soil organic carbon (SOC) in the 0–20 cm soil

A second weakness of presenting long-term averages is that they tend to give the impression that management effects are similar from year to year, which is far from being the case.

This is illustrated in Figures 15–17, which show the effects of management on crop yields in selected seasons for three of the case studies. Residue retention can either increase or decrease crop growth and, in some seasons, there can be interactions between residue management and N inputs.

Residue thresholds for improving soil carbon contents and increasing water availability

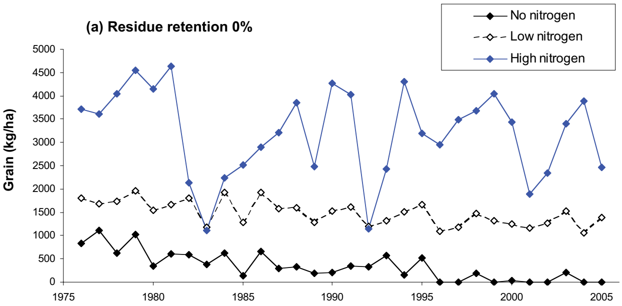
A specific aim of the study was to derive the minimum residues needed to improve soil carbon contents and increase water availability. The results show that it is not straightforward to evaluate the effects of residue management on crop productivity and components of the water balance. There is much year-to-year variation, deriving in part from the rainfall (e.g. Figure 14). More difficult to account for are carryover effects that can result in the effects of retaining residues on crop yields changing from positive to negative in different years (see Figures 15–17). It is therefore not possible to adequately summarise the effects of residue retention beyond long-term averages as shown for crop yields in Figures 2–5 and for water balance components in Figures 6–9.

In the case of SOC, there are clear trends arising from residue management as shown in Figures 10–13. While these trends are not linear, they are sufficiently regular to suggest further analysis is warranted.

The trend in SOC for each treatment was calculated as the rate of change in SOC (kg/ha/year). This was determined as:

Change in SOC = $(SOC_{final} - SOC_{initial})$/number of years simulated

The change in SOC was then examined to determine the effects of residue retention (Figures 18–21).


(a) Residue retention 0%

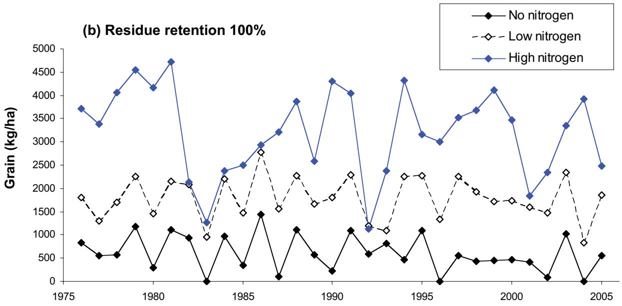

(b) Residue retention 100%

Figure 14. Case study 1—Dan. Seasonal variation in grain yields showing effects of declining fertility for the low nitrogen input systems where there is no retention of residues.

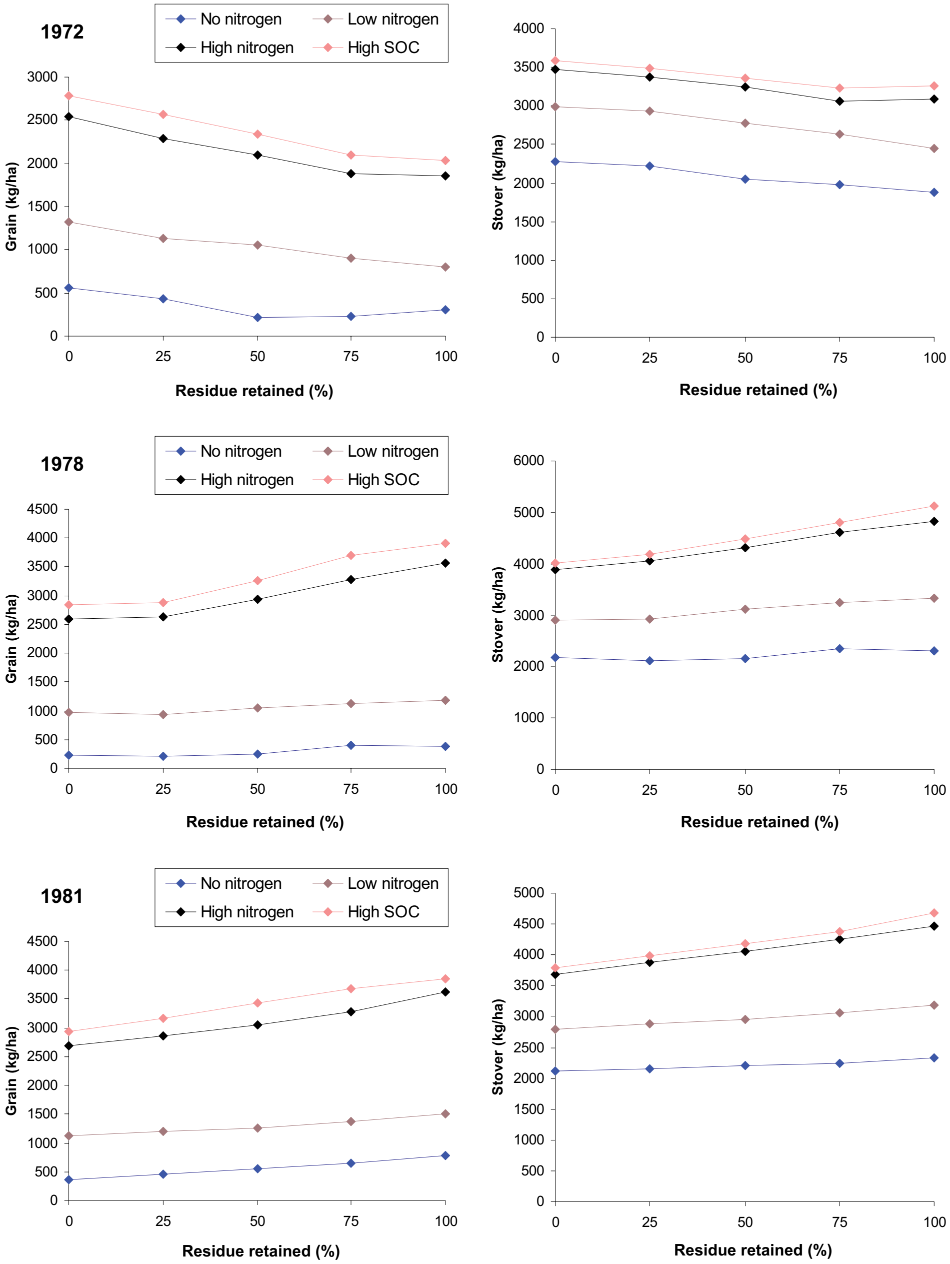


Figure 15. Case study 2—Makoholi. Effects of residue and soil fertility management (SOC = soil organic carbon) on crop yields in selected seasons (1972, 1978 and 1981)

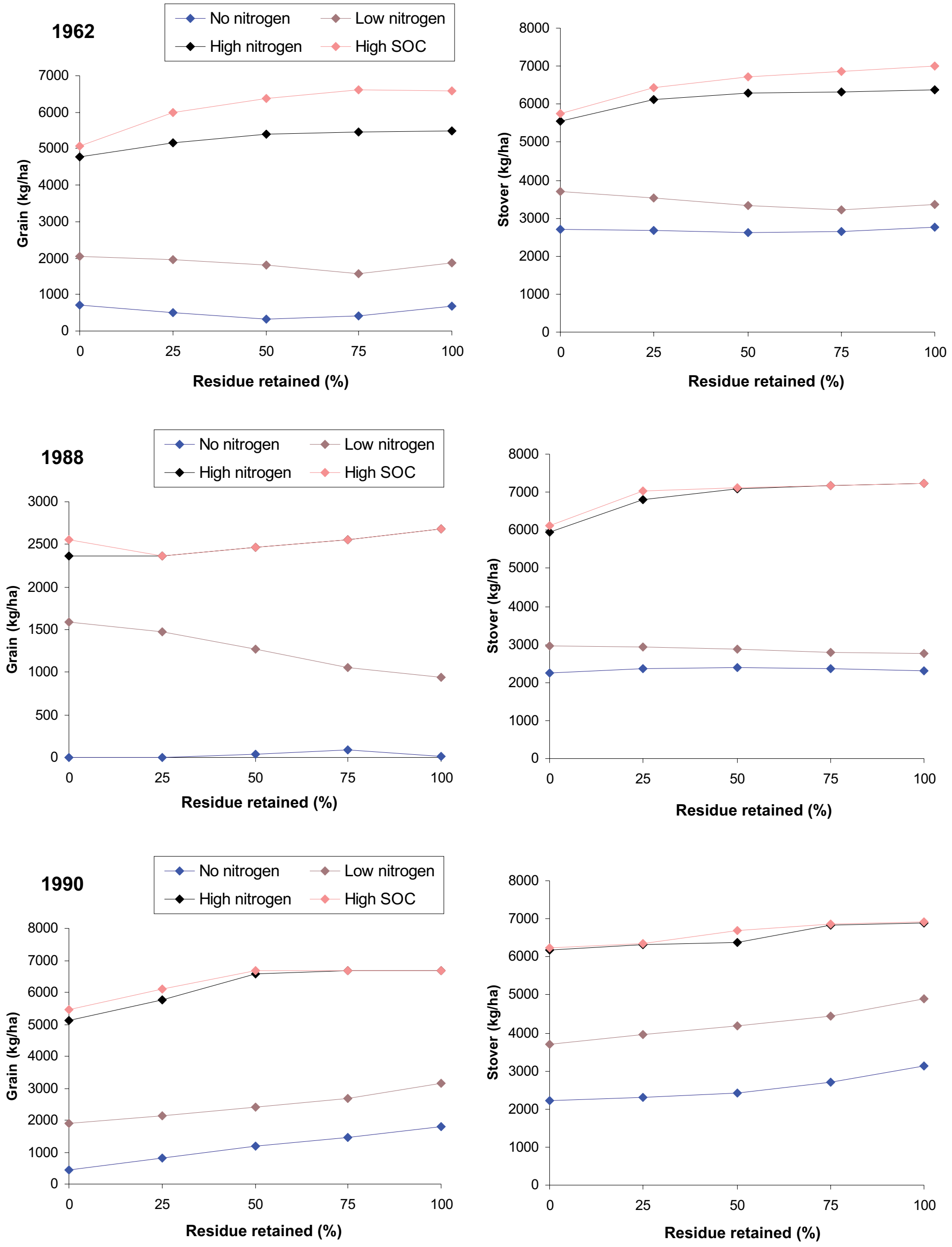


Figure 16. Case study 3—Dalby. Effects of residue and soil fertility management (SOC = soil organic carbon) on crop yields in selected seasons (1972, 1978 and 1981)

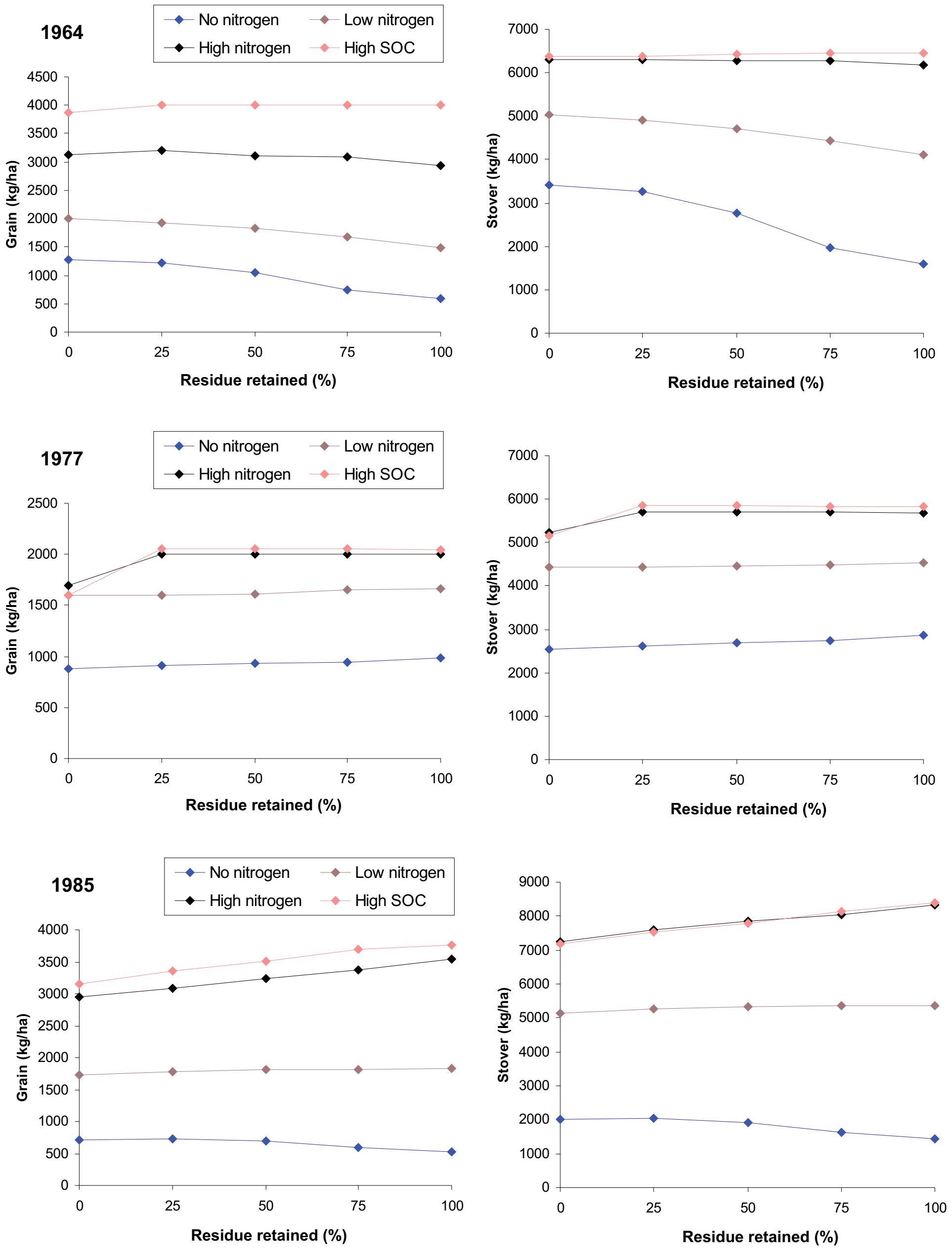


Figure 17. Case study 4—Dalby (wheat). Effects of residue and soil fertility management (SOC = soil organic carbon) on crop yields in selected seasons (1972, 1978 and 1981)

To explain these figures, the results for Makoholi (Figure 19) are taken as an example. The topmost plot shows that there is a level of residue retention that can maintain the SOC content (i.e. change in SOC is zero). For the high N input, this is approximately 65% residue retention, for the low N input it is about 95%, but for the zero N input there is no level of residue retention that can maintain SOC content.

The middle graph shows the data plotted against average amount of residues retained (kg/ha) rather than residue retention as a percentage. This results in the three N-input treatments coming together. They do not totally converge because there are effects due to carbon in roots as well as in the above-ground residues. Note that the scenarios for the low N inputs are displaced to the right of the high N treatments, reflecting the smaller mass of roots under N-limited conditions (see Figure 22). On this basis, it is clear that an annual input of about 2,500 kg/ha of above-ground residues is needed to maintain the initial SOC content of this soil.

The bottom plot in Figure 19 compares the effect of initial SOC content. Whereas 2,500 kg/ha of residues is enough to maintain the SOC of this soil at 0.5%, almost 4,000 kg/ha is required to maintain it at 0.75% and this requires close to 100% retention of residues.

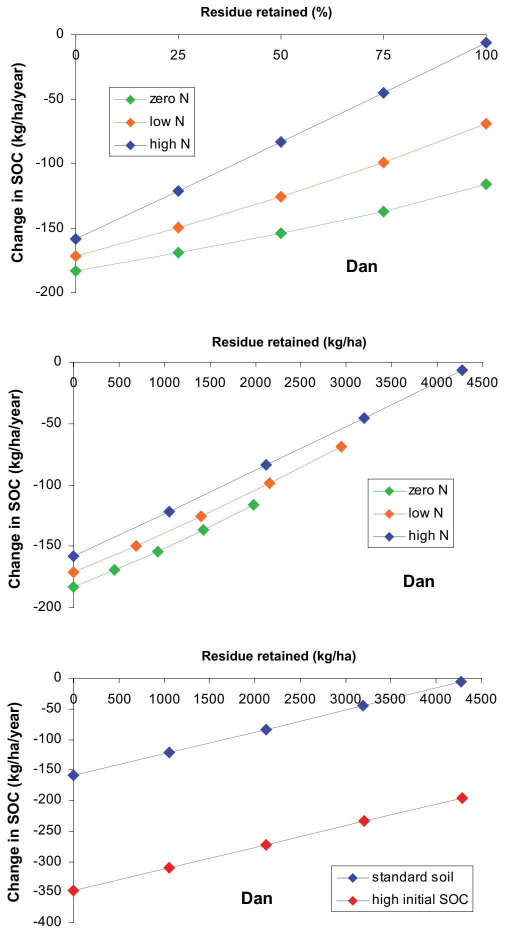


Figure 18. Case study 1—Dan. Effects of residue retention on rate of change in soil organic carbon (SOC) in 0–20 cm soil layer

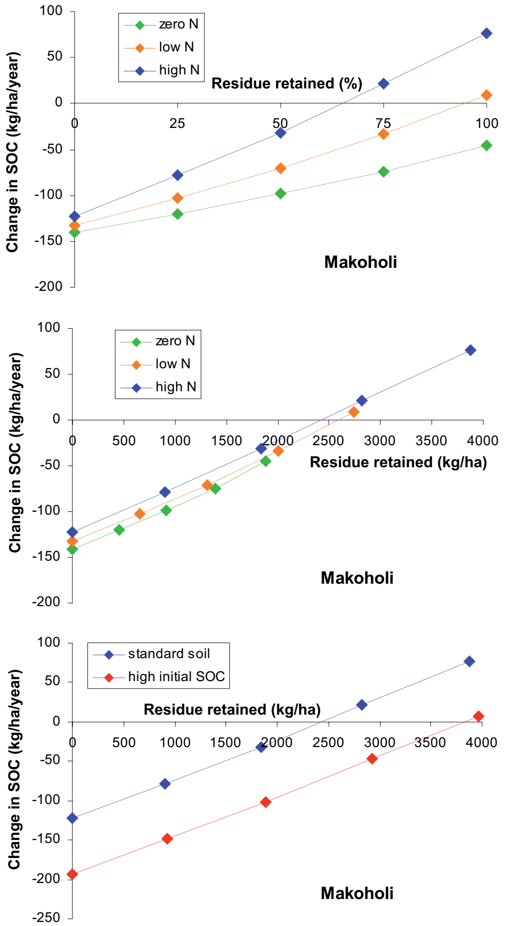


Figure 19. Case study 2—Makoholi. Effects of residue retention on rate of change in soil organic carbon (SOC) in 0–20 cm soil layer

For the standard Dan soil, which has initial SOC of 0.7%, none of the treatments provides enough residues to maintain SOC content (Figure 18). Seemingly, about 4,500 kg/ha is required and only 100% retention for the high N input approaches this.

For the Dalby scenarios, the initial SOC was 0.8%. With high N-input systems, this could be maintained with about 3,500 kg/ha of maize or wheat residues, which is obtained by retaining about 60% of residues (Figures 20 and 21). For the low N input systems, 100% residue retention is required to come close to maintaining SOC content, while with zero N input it is impossible to provide enough carbon. If the initial SOC content was increased to 1.2%, none of the treatments could maintain the SOC content.

Figure 22 illustrates the variation in root growth relative to above-ground residues (stover). This figure shows the long-term average production and thus smooths out much of the noise that exists in the data for individual seasons. Clearly, APSIM predicts that sub-optimal conditions reduce root growth as well as above-ground growth. Also, the figure shows that the proportionality between roots and stover is similar for maize and wheat, and that the relationship is robust between the different locations.

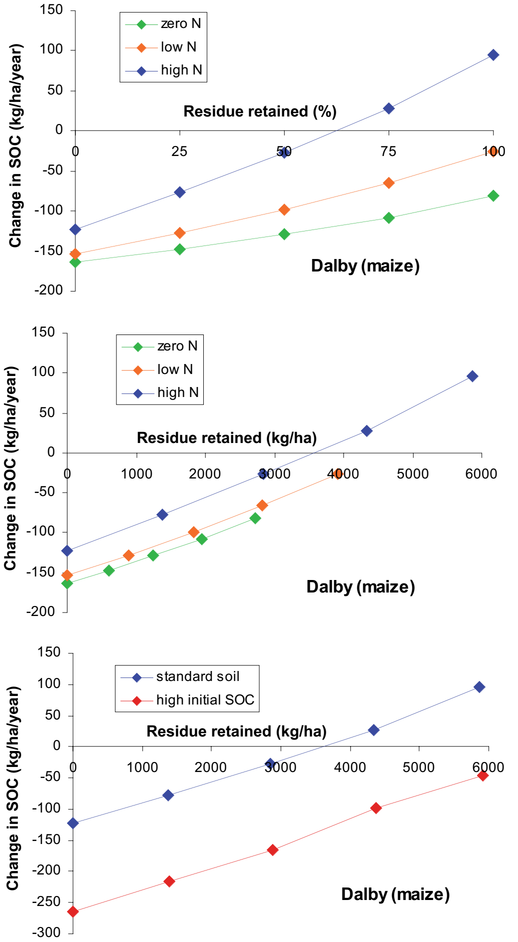


Figure 20. Case study 3—Dalby (maize). Effects of residue retention on rate of change in soil organic carbon (SOC) in 0–20 cm soil layer

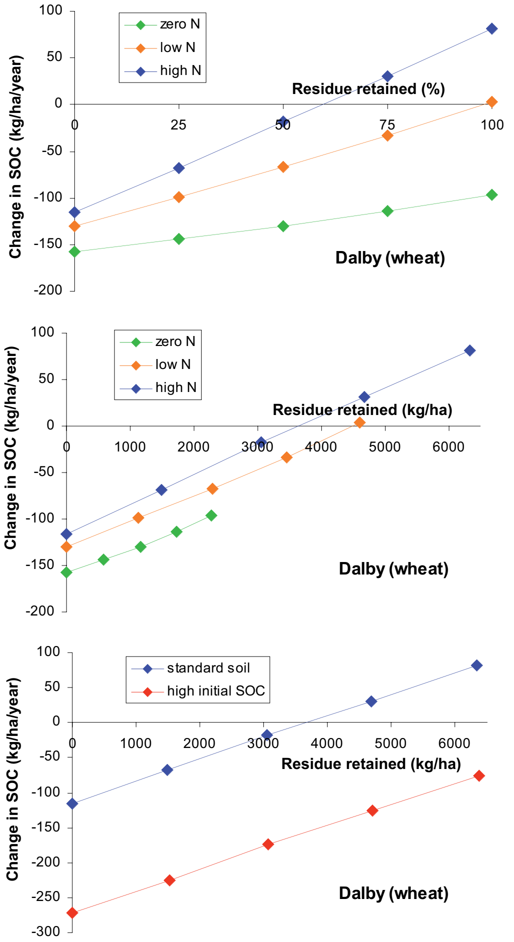


Figure 21. Case study 4—Dalby (wheat). Effects of residue retention on rate of change in soil organic carbon (SOC) in 0–20 cm soil layer

Measured data for well-grown wheat crops in south-eastern Queensland indicate root growth amounts to some 2,000 kg/ha (R.C. Dalal, pers. comm.). The predicted long-term averages will include crops that suffered from water stress in years of below-average rainfall. Thus, the values shown in Figure 22 for the high fertility scenarios of about 1,500 kg/ha are considered to be reasonable estimates.

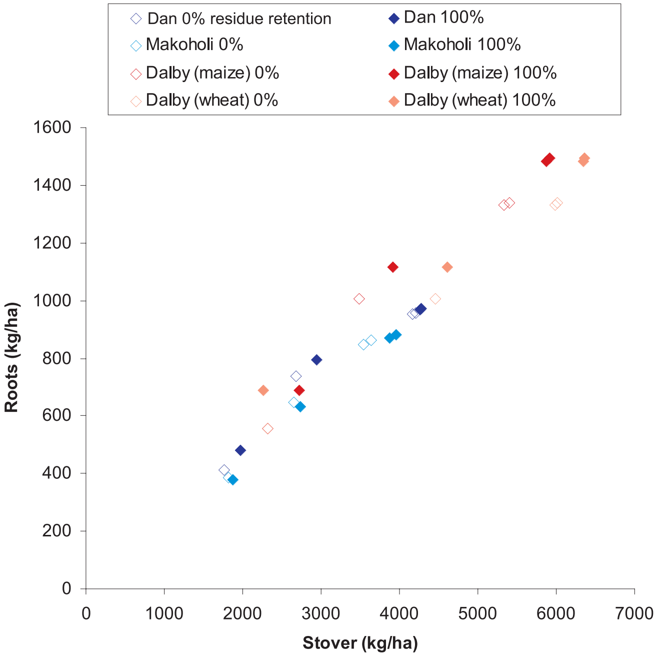


Figure 22. Comparison of roots and stover production. Data plotted are the long-term averages for the four fertility levels for each case study. Note that only the extremes of the residue retention treatments are shown and these are distinguished as open (0% retention) or solid (100% retention) symbols.

Probert, M.E. 2007. Modelling minimum residue thresholds for soil conservation benefits in tropical,
semi-arid cropping systems. Canberra, ACIAR Technical Reports No. 66.

Discussion

Limitations and assumptions

In any modelling study, it is important that the limitations and assumptions be recognised. In this study, the use of APSIM assumes that the functionality in the SOILWAT2, SOILN2 and SURFACEOM modules is capable of capturing the essential aspects of conservation agriculture. This functionality includes:

- effects of surface cover provided by crop residues on soil evaporation and run-off (by means of adjusting the curve number)
- dynamics of soil organic matter in response to inputs of carbon in roots and above-ground residues. Mineralisation of N will reflect the changing SOC content of the soil.

The model does not, however, change the soil's water characteristics in response to changed SOC content, and especially any effect of SOC on infiltration rate.

The other obvious omission from this study is the important contribution of erosion to soil degradation. For low-input farming systems with no retention of residues, the decline in SOC and crop yields (as shown in Figures 10 and 14 for the Dan location) is very familiar as the situation that prevails in subsistence farming systems in the semi-arid tropics of Africa. McCown and Jones (1992) referred to the degradation of these farming systems as 'the poverty trap'. Without protection of the soil surface, the run-off component will be higher and soil losses will increase. Because the surface soil contains much of the soil organic matter and other nutrients, erosion exacerbates the declining soil fertility. Ignoring erosion will tend to underestimate the degradation that is occurring and the rate at which crop productivity declines.

Are the results credible?

The credibility of models is usually tested by their predictive performance against measured datasets. Although that was outside the scope of the present study, it is nonetheless of interest to put the outputs shown in Figures 2–13 in the context of published experimental data. Two studies of wheat systems on Vertosols in Queensland are pertinent.

First, a long-term experiment at Hermitage investigated the effects of stubble and tillage management (Marley and Littler 1989). The stubble management treatments were either to burn or retain, that is, zero or 100% residue retention. The tillage treatments were either conventional tillage with stubble incorporation, or no-till with crop residues remaining above-ground. Subsequently, Probert et al. (1995) used the experimental data to test the performance of APSIM and CENTURY models. Their summary of the experimental results was

> … the effects of the tillage and stubble management treatments varied from season to season. In years of low rainfall, water is the main limitation and stubble retention improves fallow efficiency for conservation of water, which is reflected in improved grain yields. Nitrogen limitations become greater in years of good rainfall with stubble retained treatments being more responsive to applied N.

On the initially fertile Vertosol, none of the treatments were able to maintain the soil organic matter content of the soil. The models did a satisfactory job in predicting the decline in soil organic matter that occurred and the reduction through time in the ability of the soil to mineralise and accumulate nitrate-N during the fallows.

The second experiment is the Soil Fertility Restoration Experiment at Warra. On this Vertosol with depleted SOC following about 70 years of cropping, the only treatments that increased SOC were the four-year grass plus legume leys (Dalal et al. 1995). During the early years of the experiment, continuous wheat cropping with 100% residues retained maintained SOC where N fertiliser was used, but SOC declined without N inputs.

Thus, the changes in SOC predicted for the wheat system (Figures 13 and 21) are in general agreement with these experimental results.

The second aspect of the model outputs that requires comment is the predicted drainage and run-off. The average annual excess water (that is drainage plus run-off) under good N nutrition at Dalby averages 143 mm for the wheat system and 84 mm for the maize system. For the two African locations, excess water is even higher—260 mm at Makoholi and 333 mm at Dan.

Keating et al. (2002) used APSIM to model the water balance of dryland farming systems in the Murray–Darling Basin. One of their systems was annual wheat cropping with input of 80 kg N/ha as fertiliser to each crop. They removed 75% of residues to mimic grazing. For an annual rainfall of about 700 mm, they estimated excess water of approximately 150 mm, which is very similar to the average predicted here.

Where N inputs are lower, crop growth is restricted, so the transpiration component is smaller and excess water must increase.

At the African sites, excess water is predicted to be higher than at Dalby. This reflects both the rainfall (which is considerably higher at Dan) and the difference between the sandy soils at the African locations and the Vertosol at Dalby. The larger plant available water capacity of the Vertosol means that the dry soil zone that is created under the crop provides some protection against drainage when the soil next wets up.

Modelling versus experimentation

It is noted in the introduction to this report that there is a lack of experimental data showing long-term benefits of residue retention in mixed livestock–cropping systems in the semi-arid tropics. The output from the modelling undertaken in this study suggests that this situation is likely to continue. The long-term average crop productivity shown in Figures 2–5 indicates that the 'average' effects are generally small. The case study with the largest effect of residue retention on crop yield is the maize system at Dalby; with high N inputs at this site, average grain yields were increased from 3,365 to 4,483 kg/ha as residue retention increased from zero to 100%. It is noteworthy that this is the case study with the smallest amount of excess water.

Figures 15–17 illustrate that the responses to residue retention are not consistent from season to season. When the effects are averaged across seasons to obtain the 'long-term average', positive and negative effects will tend to cancel one another.

However, reality is likely to be even more complicated than indicated by Figures 15–17. These were selected on the basis that there are apparently smooth responses to residue retention. Many other seasons have responses that are far from smooth. Reasons for this are to be found in the carryover effects from season to season, effects that can be due to either water or mineral-N.

A simple experiment to investigate effects of residue retention can commence with initial water and mineral-N uniform across all treatments. However, as the experiment progresses to study the longer-term effects of different residue-management treatments, the treatments all have water and mineral-N contents that behave independently. Furthermore, there are many interactions. Treatments that increase drainage may also result in loss of nitrate via leaching.

Even deciding on appropriate residue-management treatments is problematic. Effects of residues on the water balance are manifested predominantly through the cover they provide. Systems where crop growth is limited by N inputs are incapable of providing as much residue as crops with adequate nutrition. Attempting to analyse the output in terms of treatments defined as percentages of residues retained is too simplistic. This is also evident in the analysis of changes in SOC (Figures 18–21); plotting the data as a function of amounts of residues (kg/ha) retained tends to bring the treatments together, whereas plotting against percentage residue retention accentuates the differences.

Residue thresholds that increase soil carbon contents and water availability

Soil organic carbon is dependent to a large degree on the inputs of carbon to the system. The outputs from the simulations exhibit marked trends in SOC (Figures 10–13) from which thresholds of residue retention can be derived where there is zero net change in SOC.

The standard soils were assumed to have initial SOC contents that were low, reflecting the consequences of typical farming systems. In the semi-arid tropics of Africa, subsistence farming systems with minimal inputs of N and little return of crop residues to the soil have severely degraded soils, so that SOC contents are low. Similarly, cropping on Vertosols in south-eastern Queensland has been exploitive, and

SOC has been depleted (for example, the experiment of Dalal et al. (1995) at Warra).

The simulations show that, where crops are adequately fertilised, there are sufficient residues to at least maintain the low SOC contents of the soil. At Dan, this required retention of all the residues; for the other case studies, the threshold was at approximately 65% retention. Where crops were less well-supplied with N, there were generally insufficient residues to maintain SOC, even with 100% retention. Only for the Makoholi case study, where initial SOC was 0.5%, was it possible to maintain SOC under the low N scenario.

Where initial SOC was 50% higher (which might represent a less-depleted soil) it becomes even more difficult to maintain the SOC content. Only for the Makoholi case study was it possible to establish a threshold at around 100% retention (Figure 19).

For crop productivity and components of the water balance, there is so much year-to-year variability that the notion of a threshold level of residue retention that provides beneficial effects is less useful than for changes in SOC. The long-term effects, as summarised in Figures 2–9, do not exhibit any level of residues (that is a threshold) where crop yields or components of the soil water balance respond to residue-management changes. A more detailed inspection reveals a complex system in which effects are not related in a simple cause–effect relationship with the imposed management of residues and fertiliser inputs—see Figures 15–17 for examples of how residue retention can have opposite effects on crop yields in different years.

Rather than seeking a threshold of residue retention, a more flexible analysis may reveal tactical management options. Such an analysis would focus on what is happening in individual seasons and attempt to identify the conditions necessary for useful management intervention.

Tillage

Conservation agriculture involves both residue retention and tillage management. All of the simulations carried out in this study were for zero-till management.

The Hermitage experiment (Marley and Littler 1989) on a Vertosol showed that, in terms of crop growth, tillage effects were less important than residue management or N inputs. On other soil types, particularly where surface crusting may be important in the partitioning of rainfall between infiltration and run-off, tillage may have greater impact. Currently the functionality of the APSIM SOILWAT2 module does not modify infiltration in response to tillage or change in SOC content. Thus, investigation of such effects was beyond the scope of the model used.

Conclusions

The simulated effects of retention of maize or wheat residues on average long-term crop production were modest. The largest effects were found for the maize system at Dalby. Judged in terms of excess water, this was the driest site.

The simulations show that residue management does have implications for SOC. The trends in SOC could be related to residue management to determine thresholds of residue retention that resulted in no change in SOC content. For soils with low initial SOC, these thresholds were approximately 60% residue retention for adequately fertilised crops, whereas for N-limited crops, even 100% residue retention failed to maintain SOC (except at the Makoholi location, which had the lowest SOC content). Where initial SOC was 50% higher, approaching 100% retention of residues was the threshold for the Makoholi location, but there were inadequate residues to maintain these higher SOC contents for the other case studies.

Optimism that ‘normal’ farming systems can sequester large amounts of carbon in the soil and thus contribute to solving the global warming problem is not supported by the results obtained in this study.

For crop yields and components of the water balance, the notion of threshold levels of residue retention (or of residues) that determine whether beneficial effects are obtained from conservation agriculture was less helpful. Variation in rainfall, and carryover effects of water and/or nitrogen, complicate the interpretation of responses. Crop yield response to residue retention can change from positive to negative. Positive effects will occur where residues reduce run-off and/or evaporation so that the crop experiences an improved water supply (generally in years of low rainfall), provided that the nutritional status is adequate.

The results from the simulations highlight that the response of such systems is complex and show why these systems are not well-suited to experimentation. It seems unlikely that carrying out ‘simple’ experiments investigating conservation cropping will lead to clear answers about the benefits of retaining crop residues.

It is widely recognised that retaining residues has large benefits in reducing soil losses. This study implies that this is likely to remain the predominant benefit from the practice.

Acknowledgment

I thank Dr A.M. Whitbread, CSIRO Sustainable Ecosystems, Brisbane, who provided the soil and weather files for the African sites, together with advice on the farming systems at these locations.

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Appendix

Properties of the three soils used in this study

(a) Dan soil

Layer number	1	2	3	4	5	6	7
Layer depth (mm)	100	100	100	300	300	300	300
Air dry (mm/mm)	0.03	0.03	0.09	0.15	0.15	0.15	0.15
LL15 (mm/mm)	0.12	0.12	0.12	0.18	0.20	0.20	0.20
LL (maize) (mm/mm)	0.12	0.12	0.12	0.18	0.20	0.29	0.29
DUL (mm/mm)	0.23	0.23	0.23	0.29	0.29	0.40	0.40
SAT (mm/mm)	0.40	0.40	0.40	0.40	0.40	0.70	0.70
swcon	0.70	0.70	0.70	0.70	0.70	1.46	1.46
Bulk density (g/cm^3)	1.46	1.46	1.46	1.46	1.46		
cn2-bare	80						
u	3						
cona	3.5						
Organic carbon (%)	0.70	0.70	0.60	0.50	0.40	0.40	0.40
finert	0.50	0.60	0.80	0.99	0.99	0.99	0.99
Soil carbon:nitrogen	14.5						
With high initial soil organic carbon							
Organic carbon (%)	1.05	1.05	0.60	0.50	0.40	0.40	0.40
finert	0.33	0.40	0.80	0.99	0.99	0.99	0.99

LL = volumetric water content at lower limit of extraction of water by crop; DUL = volumetric water content at drained upper limit; SAT = volumetric water content at saturation; swcon = the portion of water above DUL that moves within the daily time step; cn2-bare = curve number for run-off from bare soil; u and cona = the coefficients for 1st and 2nd stage evaporation; finert = proportion of organic carbon that is inert and not susceptible to decomposition.

(b) Makoholi soil

Layer number	1	2	3	4	5	6	7
Layer depth (mm)	100	100	100	150	150	200	200
Air dry (mm/mm)	0.03	0.07	0.07	0.09	0.09	0.09	0.09
LL15 (mm/mm)	0.05	0.07	0.07	0.13	0.14	0.18	0.22
LL (maize) (mm/mm)	0.05	0.07	0.07	0.13	0.14	0.18	0.22
DUL (mm/mm)	0.14	0.15	0.15	0.20	0.20	0.22	0.24
SAT (mm/mm)	0.44	0.44	0.44	0.44	0.40	0.40	0.40
swcon	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Bulk density (g/cm^3)	1.43	1.43	1.43	1.43	1.55	1.55	1.61
cn2-bare	85						
u	8						
cona	3.5						
Organic carbon (%)	0.50	0.50	0.25	0.20	0.20	0.20	0.20
finert	0.10	0.10	0.40	0.80	0.90	0.95	0.99
Soil carbon:nitrogen	14.0						
With high initial soil organic carbon							
Organic carbon (%)	0.75	0.75	0.25	0.20	0.20	0.20	0.20
finert	0.067	0.067	0.40	0.80	0.90	0.95	0.99

LL = volumetric water content at lower limit of extraction of water by crop; DUL = volumetric water content at drained upper limit; SAT = volumetric water content at saturation; swcon = the portion of water above DUL that moves within the daily time step; cn2-bare = curve number for run-off from bare soil; u and cona = the coefficients for 1st and 2nd stage evaporation; finert = proportion of organic carbon that is inert and not susceptible to decomposition.

(c) Warra soil

Layer number	1	2	3	4	5	6	7
Layer depth (mm)	100	100	100	300	300	300	300
Air dry (mm/mm)	0.10	0.20	0.20	0.20	0.20	0.20	0.20
LL15 (mm/mm)	0.22	0.22	0.23	0.24	0.26	0.27	0.28
LL (maize) (mm/mm)	0.22	0.22	0.23	0.24	0.28	0.33	
DUL (mm/mm)	0.45	0.45	0.45	0.44	0.42	0.41	0.41
SAT (mm/mm)	0.50	0.51	0.51	0.50	0.49	0.48	0.48
swcon	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Bulk density (g/cm^3)	1.30	1.30	1.29	1.31	1.35	1.36	1.36
cn2-bare	80						
u	6						
cona	4.0						
Organic carbon (%)	0.80	0.80	0.70	0.60	0.54	0.48	0.43
finert	0.50	0.50	0.75	0.90	0.90	0.99	0.99
Soil carbon:nitrogen	14.0						
With high initial soil organic carbon							
Organic carbon (%)	1.20	1.20	0.70	0.60	0.54	0.48	0.43
finert	0.33	0.33	0.75	0.90	0.90	0.99	0.99

LL = volumetric water content at lower limit of extraction of water by crop; DUL = volumetric water content at drained upper limit; SAT = volumetric water content at saturation; swcon = the portion of water above DUL that moves within the daily time step; cn2-bare = curve number for run-off from bare soil; u and cona = the coefficients for 1st and 2nd stage evaporation; finert = proportion of organic carbon that is inert and not susceptible to decomposition.