Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia

2. Soil physical fertility and carbon

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Abstract

Soil organic matter (SOM) is considered as a key indicator of sustainability, therefore measurements of SOM changes under various forms of management are needed for the development of sustainable systems. Because the measurement of total SOM is not sensitive enough to monitor short and medium term changes, techniques that measure meaningful fractions of SOM should be used. In this study both total carbon (CT) measured by combustion and labile carbon (CL) determined by oxidation with 333 mM potassium permanganate (KMnO₄) were measured. Field trials, consisting of a legume phase followed by three wheat (\textit{Triticum aestivum} L. cv. Janz) crops, were established on a degraded Ferric Luvisol (Red Earth) soil in New South Wales to investigate the effect of crop residue and fertiliser management on wheat yield, soil physical properties and SOM. Total and labile C increased following a lucerne (\textit{Medicago sativa} L. cv. Trifecta) phase, however, chickpea (\textit{Cicer arietinum} L. cv. Amethyst), barrel medic (\textit{Medicago truncatula} L. cv. Sephi) and fallow leys resulted in no increases in soil C concentrations. During the wheat phase the concentration of CL significantly increased on the treatments with wheat stubble retention. This resulted in the C Management Index (CMI), an index comparing changes in labile and total C fractions relative to an uncropped reference soil, increasing from 19 to 27. The greatest treatment effect on soil physical properties was the retention of wheat stubble on the soil surface over the summer fallow period which increased hydraulic conductivity (K) by more than 65%, relative to the stubble removed treatment. Mean weight diameter (MWD) increased from 799 to 920 mm and a significant relationship was found between hydraulic conductivity and water stable aggregates >500 μm. Soil strength at 15 cm decreased from 2713 in the non-return to 2064 kPa in the stubble retained treatments with both treatments having a similar water content at the time of measurement. Although legume species are widely used as a rotation phase, their use in combination with cereal stubble retention is more likely to improve the overall fertility of the farming system. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Disc permeameter; Hydraulic conductivity; Aggregate stability; Aggregate size distribution; Carbon; Carbon management index

1. Introduction

The organic matter content of soil is generally found to decrease rapidly following the clearing of
native vegetation and the subsequent cultivation and cropping activities. Although the total organic C of the soil declines due to cultivation, of particular concern is the decline in the more labile C fractions, which may be associated with soil nutrient dynamics (Parton et al., 1987) and have a role in the stabilisation of soil structure (Allison, 1973). Blair et al. (1995) and Conteh et al. (1997) have shown that labile C obtained by ease of oxidation can provide a very meaningful index of organic matter in soil. Furthermore, the C Management Index (CMI), calculated from changes in labile and total C fractions relative to an uncropped reference soil, was shown by Whitbread et al. (1998) to be a useful technique for describing the rundown of soil fertility of cropping lands in northern New South Wales Australia.

The importance of SOM and groundcover on soil structure are well documented and have been shown to influence infiltration (Bissett and O’Leary, 1996), aggregate stability (Chan et al., 1988), soil strength (Soane, 1990), soil water (Cantero-Martinez et al., 1995) and crop growth. The timing of crop residue addition to the system and the residue decomposition rate, have implications for subsequent crop growth and the efficiency of nutrient recovery. Residues of good grazing quality generally have fast breakdown rates. This often leads to an initial flush of microbial activity, fast decomposition rates and nutrient loss before the available nutrients are required by the subsequent crop. The use of crop residues which have slower decomposition rates result in protection of the soil surface through mulching (Tian et al., 1993), the release nutrients for longer periods and a reduction in soil and nutrient losses. Small inputs of fertiliser may be required at planting to overcome short-term nutrient deficits.

Although the benefits of conservation tillage and stubble retention practices on soil structural properties have been widely reported, the effect of such practices on soil water accumulation and wheat yield are questionable (Cooke et al., 1985; Chan and Heenan, 1996). Chan and Heenan (1996) found that the storage of soil water was higher in a stubble retained and direct drill treatments only during a dry season. They did not, however, find a significant increases in yield due to the extra stored water. Studies which examine the impact of residue management on isolated components of the farming system are common. While this approach to research has been necessary, studies which examine residue management on the overall farming system are required for better land management information. A field trial, described by Whitbread et al. (2000) is one such study. This experiment was conducted in northern NSW, Australia to examine the effects of long term cropping, legume ley crops and the management of crop residues and fertilisers on wheat yields, and soil chemical and physical fertility. The effects on physical fertility and soil C are presented here.

2. Materials and methods

2.1. Experimental design and layout

The experiment was carried out on a Ferric Luvisol (Red Earth) soil at the University of New England’s McMaster Research Station, near Warialda in northwestern NSW, Australia. This fragile soil type, representative of large areas of eastern Australia where cereal based farming occurs, is prone to structural and chemical fertility degradation.

Treatments were laid out according to a split–split–split plot design, with main plots [chickpea (Cicer arietinum cv. Amethyst), barrel medic (Medicago truncatula cv. Sephi), lucerne (Medicago sativa cv. Trifecta) and a fallow system] being laid out in blocks. These plot were then further split into fertiliser (applied and not applied) or wheat stubble management (removed or returned) treatments.

A summary of the treatments and cropping sequence is presented below:

<table>
<thead>
<tr>
<th>1992 Legume or fallow phase</th>
<th>Plot size</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 systems (chickpea, medic, lucerne, fallow)</td>
<td>(15 m × 15 m)</td>
</tr>
<tr>
<td>×3 management’s (removed, returned, grazed)</td>
<td>(15 m × 5 m)</td>
</tr>
<tr>
<td>×3 replicates</td>
<td></td>
</tr>
</tbody>
</table>
The experimental area, on a slope of <5%, had been conventionally farmed (multiple tillage operations to control weeds and prepare a seedbed) wheat–lucerne rotation (several cereal crops followed by a lucerne phase of 2–3 years) for at least 18 years and straddled an existing fenceline. One side of the fenceline, the “wheat” area had been sown to wheat for the previous 5 years. The other side of the fence, the “lucerne” area had been a grazed lucerne ley phase for 4 years preceded by cereal cropping for at least 16 years. Full details of the experimental protocol are presented in Whitbread et al. (2000). A nearby native site which had been lightly cleared and grazed was used as the reference site and was located on the same soil type and topographic position 150 m from the wheat and lucerne sites.

2.2. Water relations measurement

Soil water was measured at sowing and harvest and at several intervals during the growing season with a neutron probe water meter described in Whitbread et al. (2000). Soil moisture was also measured when hydraulic conductivity and soil strength were measured during 1994 and 1995. Neutron probe access tubes were only installed in replicate 3 of the medic, chickpea and fallow plots.

2.3. Soil structural properties

2.3.1. Hydraulic conductivity

Hydraulic conductivity was measured at tensions of 10, 20, 30 and 40 mm with disc permeameters (Perroux and White, 1988) using the method of Ankeny et al. (1991). Hydraulic conductivity was measured at the end of April in 1994–1996, prior to soil cultivation. Wheat stubble had covered the stubble returned (+R) treatments for the 5 months since harvest, while the stubble removed (−R) treatments had remained bare over this time. Soil had not been cultivated or disturbed since the pre-sowing cultivation in May of the previous year. It was not possible to measure hydraulic conductivity on all the plots in 1994, so measurements were carried out on all plots of replicate 3 which did not have fertiliser applied at sowing. It was hypothesised that the single application of fertiliser in 1993 would have a minimal effect on soil structure and the +F plots were therefore not measured. Hydraulic conductivity was measured in triplicate on each plot during 1994. However, due to large variations in the data, four measurements were made per plot in all subsequent hydraulic conductivity measurements. Prior to sowing in 1995, hydraulic conductivity was measured on all plots of replicate 3 and on the lucerne and medic plots of replicate 3 following the 1995 harvest and prior to sowing in 1996. The later were again measured prior to sowing during April 1996.

Within the uncleared reference site, four replicate hydraulic conductivity measurements were made within a 4 m² area selected to be representative of the area.

2.3.2. Aggregate stability

Two intact soil cores (72 mm internal diameter, 41 mm depth) were taken from the same positions on which hydraulic conductivity was measured with the disc permeameters. The metal cores were inserted immediately following the hydraulic conductivity measurement, but were not removed from the soil for 24 h to allow drying and to minimise damage to the soil cores. The samples were air dried and, in order that all soil samples had a similar energy input during crushing, the soil was gently crushed on a board with small ridges on the side to maintain a 4 mm gap between the board and the roller. The samples were then sieved to <4 mm and large particles of organic matter removed. Aggregate stability to wetting was measured using a wet sieving technique with five sieve sizes (125, 250, 500, 1000 and 2000 μm). Wet sieving was undertaken by placing on top of the nest of five sieves a 30 g soil sample, immersing the sieves in water and sieving for 10 min with a vertical amplitude of 18 mm at 30 movements per minute.

The aggregate size distribution was measured by a dry sieving technique. The soil samples had the same
pre-treatment as those used for wet sieving. Soil samples (30 g) were placed on the largest mesh sieve of the set used in wet sieving. The sieve was gently vibrated by hand until soil stopped passing through the mesh, generally after 30–40 s. Soil which passed through the sieve was placed on the next largest sieve and the shaking procedure repeated until all five sieves had been used. Soil which remained on each sieve was weighed, placed in a plastic vial and stored. Mean weight diameter of the dry sieved soils (DMWD) and the wet sieved soils (WMWD) were each calculated after Kemper and Rosenau (1986). Water stable aggregates (WSA) >500 μm were calculated as the proportion of soil that did not pass through the 500 μm sieve during wet sieving.

Aggregate size distribution and stability were determined on all soil samples collected during the 1994 hydraulic conductivity experiment (i.e., all the non-fertilised plots of replicate 3) by dry and wet sieving, respectively. Due to time constraints, only soil samples from the medic treatments were analysed from the April 1995 and 1996 experiments. These cores were selected to cover a range of infiltration rates to investigate the aggregate stability and distribution of the widest range of treatment differences. Soil cores were also collected in the reference area from the same positions as where hydraulic conductivity was measured.

2.3.3. Soil strength

Resistance to penetration was measured prior to sowing in May 1995 and following harvest in December 1995 using a cone penetrometer (basal diameter of 12 mm, 60° cone) with an ultrasonic depth gauge. Penetration was measured in 5 mm increments to 0.5 m depth on all plots in replicate 3. Within the centre of each plot, a 1 m² area was chosen and 10 separate penetration resistances were measured. Plots with neutron probe access tubes were measured for water content. Due to the large variation associated with soil strength data, the seven measurements closest to the mean were selected from the 10 sets of data collected in each plot. Resistance to penetration was also measured following harvest 1995 on all plots of replicate 3. The number of replicates within the 1 m² area in the centre of each plot was reduced from 10 to 5 with the four most representative measurements being selected for analysis. In order to analyse both sets of data, the soil strength was averaged across the 30–50, 50–100, 100–150, 150–200, 200–250, 250–400 and 400–500 mm depths. These depth intervals were chosen to represent similar areas of the soil strength curve. Water content was statistically analysed from the chickpea, medic and fallow plots but not in the lucerne treatments due to missing access tubes.

2.4. Total C, labile C and light fraction SOM measurements

The determination of C_T and C_L was carried out on a selection of the 1993 soil samples which covered the three replicates of the system and management treatments. Intact soil samples collected from the medic treatments at the time of the disc permeameter measurements in 1995 and 1996 were subsampled, sieved and analysed in duplicate for C_T and C_L.

Subsamples of the <2 mm sieved material were taken and ground to <500 μm and the C_T measured in an automatic nitrogen and C analyser mass spectrometer system (ANCA-MS). The more labile soil organic C in the whole soil samples and each particle size fraction was measured by oxidation with 333 mM KMnO₄ (Blair et al., 1995).

The C_T, measured by combustion, and the amount of oxidising agent consumed by the KMnO₄ are used to calculate two fractions of organic C: the two fractions are labile C (C_L) which is equal to the C oxidised by 333 mM KMnO₄ and non-labile C (C_NL) which is equal to the C not oxidised by 333 mM KMnO₄. Since the continuity of C supply depends on both the total pool size and the lability (the labile pool size), both are taken into account in the soil of interest and an uncultivated reference soil in deriving a CMI (Blair et al., 1995). On the basis of changes in C_T between a reference site and the cropped site a C Pool Index (CPI) was calculated as CPI = C_Tcropped/C_Treference. On the basis of changes in the proportion of C_L (i.e., L=C_L/C_NL) in the soil, a Lability Index (LI) was determined as LI=L_cropped/L_reference. These two indices were used to calculate a CMI=CPI×LI×100 (Blair et al., 1995). The reference sample was collected from a nearby uncultivated, uncleared area which was covered by native vegetation.

The light fraction of SOM was separated from the remainder of the soil by physical separation based on density. Only pre-sowing soil samples collected in
1995 were analysed and these had undergone the same pre-treatment as those that were used for the wet and dry sieving (rolled and sieved to <4 mm). The separation medium was prepared by dissolving reagent-grade sodium-polytungstate, $\text{Na}_6(\text{H}_2\text{W}_{12}\text{O}_{40})\cdot\text{H}_2\text{O}$, in distilled water and adjusting the density to 1.6 mg m$^{-3}$. The procedure closely followed that of Golchin et al. (1994) except that soil samples were sieved to <4 mm rather than 2 mm.

2.5. Statistical analyses

Data from this experiment were subjected to a split–split–split plot analysis of variance, with main plots (chickpea, medic, lucerne and fallow systems) in blocks then split according to management (removed, returned, grazed). Residuals were examined for homogeneity and transformed if necessary. The soil strength, hydraulic conductivity and aggregate stability measurements were confined to replicate 3 and statistically analysed using the legume management systems to estimate the error. The wheat stubble removed versus returned treatment was balanced over the pre-wheat legume management system (removed, returned and grazed) and fertiliser treatment combinations. This allowed the legume or fallow system by fertiliser interaction to be used to estimate error (i.e., differences amongst wheat stubble removed versus returned treatment effects). Mean separation was determined using Duncan’s multiple range test and is depicted in the tables and using lower case letters. All means were separated at $p \leq 0.05$.

3. Results

3.1. Soil carbon

Prior to sowing the 1993 wheat crop, soil samples from all plots were analysed to determine the influence that the pre-wheat legume/fallow system and its management had on soil C. The reference samples, which were collected from a nearby native area, were used to calculate the LI, CPI and CMI for each treatment. The long term cropping of this site resulted in declines in $C_L$ of 68–80% and declines in $C_T$ of 71–76% relative to the original reference concentrations of C.

Following the legume or fallow phase, both $C_L$ and $C_T$ were significantly higher following the lucerne rotation resulting in a CMI of 33. The chickpea, medic and fallow systems had similar C levels and CMIs of around 20 (Table 1). The management of the residues from the legume and fallow systems had no effect on $C_T$ or $C_L$ (data not presented).

Soil samples from intact cores collected from the medic treatments prior to cultivation and sowing of the 1995 and 1996 wheat crops were also analysed for $C_T$ and $C_L$. In 1995 the retention of stubble from the two previous wheat crops had no significant effect on $C_T$ but significantly increased $C_L$ which resulted in a significantly higher CMI of 18 (Table 2). At the time of sampling, the straw from the 1994 wheat crop had not been incorporated so that essentially only the 1993 wheat stubble and the roots from the 1994 wheat crop was contributing to soil C levels. In 1996 after the two seasons of wheat stubble incorporation and the surface retention of the 1995 wheat stubble, $C_L$ was significantly higher on the returned than the removed stubble.

Table 1
The effect of the legume or fallow systems on total ($C_T$), labile ($C_L$), non-labile ($C_{NL}$) carbon ($C_T$), lability ($L$), LI, CPI and the CMI at pre-sowing 1993

<table>
<thead>
<tr>
<th></th>
<th>$C_L$ (mg g$^{-1}$)</th>
<th>$C_{NL}$ (mg g$^{-1}$)</th>
<th>$C_T$ (mg g$^{-1}$)</th>
<th>Indices$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>Reference</td>
<td>5.31</td>
<td>19.91</td>
<td>25.22</td>
<td>0.21</td>
</tr>
<tr>
<td>Lucerne</td>
<td>1.71a</td>
<td>5.70a</td>
<td>7.41a</td>
<td>0.30</td>
</tr>
<tr>
<td>Chickpea</td>
<td>1.07b</td>
<td>5.08a</td>
<td>6.11b</td>
<td>0.21</td>
</tr>
<tr>
<td>Medic</td>
<td>1.15b</td>
<td>5.02a</td>
<td>6.17b</td>
<td>0.23</td>
</tr>
<tr>
<td>Fallow</td>
<td>1.08b</td>
<td>5.29a</td>
<td>6.36b</td>
<td>0.21</td>
</tr>
</tbody>
</table>

$^a$ Means followed by the same letter within columns are not significantly different according to Duncan’s Multiple Range Test at $p \leq 0.05$.

$^b$ $L = C_L/C_{NL}$, $LI = L_{cropped}/L_{reference}$, $CPI = C_T_{cropped}/C_T_{reference}$, $CMI = CPI \times LI \times 100$. 
treatments and both had increased from the 1995 \( C_L \) levels. The \( C_T \) levels had not changed significantly from the previous season. The higher \( C_L \) in the stubble retained treatments resulted in an increase in the CMI to 27 (Table 2). Increases in the \( C_L \) concentration of the removed stubble treatment between 1995 and 1996 are presumably due to below ground inputs of C from the wheat crops.

Light fraction SOM, determined through densitometric fractionation, showed the amount of free, or relatively unprocessed organic matter in soil. There was no significant difference in light fraction SOM between the returned and removed wheat stubble treatments (421–437 \( \mu g/g \), respectively) in the soil samples from the medic treatments in 1995. However, the addition of fertiliser significantly increased light fraction SOM from 385 \( \mu g/g \) soil in the –F treatment to 474 \( \mu g/g \) soil in the +F treatment.

### 3.2. Soil physical properties

#### 3.2.1. Hydraulic conductivity

Hydraulic conductivity (\( K \)) measured on the reference site indicated very high infiltration rates at the tensions of 10 and 20 mm. Long term cropping practices reduced hydraulic conductivity by at least 50% from its original levels due to declines in soil structural properties (Table 3).

During the field trial, the management of wheat stubble had the greatest impact on \( K \). The hydraulic conductivity measured at 10 mm tension (macropores >3 mm) at pre-sowing in every year of the trial increased

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### Table 2

The effect of wheat stubble removed (−R) and stubble returned (+R) on total (\( C_T \)), labile (\( C_L \)), non-labile (\( C_{NL} \)), lability (L), LI, CPI and the CMI prior to cultivation and sowing in 1995 and 1996

| Year | Stubble management | \( C_L \) (mg g\(^{-1}\)) | \( C_{NL} \) (mg g\(^{-1}\)) | \( C_T \) (mg g\(^{-1}\)) | Indices\(^a\) \\
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( L )</td>
<td>LI</td>
<td>CPI</td>
<td>CMI</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>5.31</td>
<td>19.91</td>
<td>25.22</td>
<td>0.21</td>
</tr>
<tr>
<td>1995</td>
<td>−R</td>
<td>0.89c</td>
<td>5.52a</td>
<td>6.41a</td>
<td>0.16c</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>1.01b</td>
<td>5.86a</td>
<td>6.87a</td>
<td>0.17c</td>
</tr>
<tr>
<td>1996</td>
<td>−R</td>
<td>1.04b</td>
<td>4.89a</td>
<td>5.93a</td>
<td>0.22b</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>1.38a</td>
<td>5.13a</td>
<td>6.51a</td>
<td>0.27a</td>
</tr>
</tbody>
</table>

\(^a\) Means followed by the same letter within columns are not significantly different according to Duncan’s Multiple Range Test at \( p \leq 0.05 \).

\(^b\) \( L = C_L/C_{NL}, \ LI = L_{cropped}/L_{reference}, \ CPI = C_T_{cropped}/C_T_{reference}, \ CMI = CPI \times LI \times 100 \).

### Table 3

Hydraulic conductivity (\( K \)) (mm h\(^{-1}\)) on stubble removed (−R) and returned (+R) treatments at pre-sowing 1994, 1995, 1996 and post-harvest 1995

<table>
<thead>
<tr>
<th>Tension (mm)</th>
<th>Stubble management</th>
<th>Hydraulic conductivity (mm h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>−R</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>115a</td>
</tr>
<tr>
<td>20</td>
<td>−R</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>31a</td>
</tr>
<tr>
<td>30</td>
<td>−R</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>16a</td>
</tr>
<tr>
<td>40</td>
<td>−R</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>+R</td>
<td>10a</td>
</tr>
</tbody>
</table>

\(^a\) Means followed by the same letter within columns at each tension are not significantly different according to Duncan’s Multiple Range Test at \( p \leq 0.05 \).
by more than 70% with the return of wheat stubble (Table 3). The other pore size classes on the stubble returned treatments also increased significantly resulting in a soil with a better pore size distribution.

Over the 1995 growing season there was a 61 and 33% increase in hydraulic conductivity measured at 10 mm tension from sowing until harvest on the stubble removed and returned plots, respectively. Hydraulic conductivity measured at sowing 1996, 5 months after harvest 1995, illustrated the effect that stubble cover had on soil structure. The plots on which stubble cover had been retained maintained the hydraulic conductivity at the harvest 1995 levels, while the hydraulic conductivity on plots from which stubble had been removed generally declined and remained low. A similar trend occurred at the higher tensions of 20, 30 and 40 mm.

The type of legume or fallow systems grown prior to the wheat phases influenced hydraulic conductivity in the treatments on which wheat stubble was retained. In 1994, the medic and fallow systems had higher hydraulic conductivity values than the lucerne and chickpea systems, but all systems had similar hydraulic conductivity values when wheat residue was removed (Table 4). In 1995, lucerne had the highest hydraulic conductivity followed by the medic, fallow and chickpea systems, respectively (Table 4). Hydraulic conductivity of the chickpea, medic and fallow systems had substantially decreased in comparison to the 1994 figures whilst it was maintained on the lucerne plots. In all systems the 2 years of stubble removal resulted in hydraulic conductivity of below 25 mm h$^{-1}$. Once again chickpea resulted in the lowest $K$. Although fertiliser significantly increased wheat yields (Whitbread et al., 2000), the benefits of extra crop stubble and enhanced root growth were not reflected in higher $K$.

3.2.2. Aggregate size distribution and stability

The reference soil provided a baseline measure of aggregate size distribution and stability prior to cropping. The size distribution of the reference soil obtained by dry sieving was similar to that of the cropped soils. Wet sieving of the reference soil revealed that there were more stable macroaggregates in the 1000 and 2000 μm aggregate size classes and a larger MWD (Table 5) indicating a more structurally stable soil. The decline in the MWD from dry sieving to wet sieving showed that the reference soil maintained its aggregate stability by only declining by 14%, compared to at least a 39% decline associated with the cropped soils.

Table 4
The interaction between legume or fallow systems and wheat stubble management on hydraulic conductivity ($K$) (mm h$^{-1}$) at 10 mm tension during 1994 and 1995

<table>
<thead>
<tr>
<th>Legume/fallow</th>
<th>Hydraulic conductivity (mm h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td>−R</td>
</tr>
<tr>
<td>Lucerne</td>
<td>43c</td>
</tr>
<tr>
<td>Chickpea</td>
<td>28c</td>
</tr>
<tr>
<td>Medic</td>
<td>32c</td>
</tr>
<tr>
<td>Fallow</td>
<td>26c</td>
</tr>
</tbody>
</table>

* Means followed by the same letter within each year are not significantly different according to Duncan’s Multiple Range Test at $p \leq 0.05$.

Table 5
The effect of the legume or fallow systems on the proportion of aggregates contained on the 2000 and 1000 μm sieves, the MWD (μm) after dry and wet sieving, and the percentage decline in MWD due to wet sieving of the soils sampled in 1994 and the reference

<table>
<thead>
<tr>
<th>Legume/fallow</th>
<th>Dry sieve</th>
<th>Wet sieve</th>
<th>Decline in MWD$^b$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000%</td>
<td>1000%</td>
<td>MWD (μm)</td>
</tr>
<tr>
<td>Reference</td>
<td>9.2</td>
<td>13.0</td>
<td>718</td>
</tr>
<tr>
<td>Lucerne</td>
<td>17.5a</td>
<td>11.3a</td>
<td>930a</td>
</tr>
<tr>
<td>Chickpea</td>
<td>10.8b</td>
<td>8.2b</td>
<td>699b</td>
</tr>
<tr>
<td>Medic</td>
<td>9.6b</td>
<td>8.6b</td>
<td>674b</td>
</tr>
<tr>
<td>Fallow</td>
<td>9.2b</td>
<td>8.3b</td>
<td>656b</td>
</tr>
</tbody>
</table>

$^a$ Means followed by the same letter within columns are not significantly different according to Duncan’s Multiple Range Test at $p \leq 0.05$.

$^b$ Decline in MWD$=|(\text{MWD after dry sieving}−\text{MWD after wet sieving})/\text{MWD after dry sieving})|$. 
In the field experiment, the legume or fallow phases influenced the size and stability of soil aggregates collected in 1994. Soil from the lucerne treatments had the greatest proportion of macroaggregates which resulted in a higher MWD of both the wet and dry sieved soil. This lucerne treatment also showed a 47% decline in the MWD from dry sieved MWD to wet sieved MWD compared to an average 40% decline for the other treatments (Table 5). Whether the legume residues were removed, returned or grazed did not affect aggregate stability.

Soils samples collected in 1995 showed that dry aggregate size increased on both the stubble removed and retained treatments with each successive season. The removal of wheat stubble resulted in decreases of 13–19% in the dry sieved MWD and decreases of 3–13% in the wet sieved MWD (Table 6). The water stable aggregates that were >500 μm in diameter also indicated that there were more water stable macro-aggregates in the stubble retained treatments, although this was only significant during 1994. There were no other significant interactions between aggregate size distribution and the other treatments.

A stepwise regression technique was used to determine the relationship between macropore hydraulic conductivity and aggregate measurement for the 1995 data and the following equation gave the best correlation.

\[
\text{Hydraulic conductivity (10 mm)} = -253 + 28.8 (D2000) + 46.7 (D500) + 0.289 (\text{WMWD}), \quad r^2 = 0.72^{***} (1)
\]

where D2000 is the mass of soil retained on the 2000 μm sieve after dry sieving, D500 the mass of soil retained on the 500 μm sieve after dry sieving, and WMWD is the mean weight diameter of soil after wet sieving.

Hydraulic conductivity was highly correlated to the initial aggregate size distribution which was significantly increased by wheat stubble cover. Presumably, hydraulic conductivity is also highly correlated to aggregate stability but measurement of aggregate stability by wet sieving failed to find differences between stubble removed and returned treatments despite up to a 5-fold increase in hydraulic conductivity from stubble retention. Field observations indicated that plots with stubble removed developed a soil crust or ‘washed-in zone’ which probably tended to dominate surface infiltration rates. The soil surface of plots on which stubble remained appeared to be well aggregated and hence have higher K.

### 3.2.3. Soil strength

The management of wheat stubble after the 1993 and 1994 wheat crops greatly influenced soil strength values. Penetration resistance was found to be higher at all depths in the stubble removed treatment. The soil water content of the chickpea, medic and fallow systems at pre-sowing, measured at 0.1 m intervals to 0.5 m depth, increased from 0.188 m m⁻¹ at 0.1 m depth to 0.272 m m⁻¹ at 0.5 m depth. There was no significant difference found between the stubble removed and returned treatments. The soil water at the post-harvest sampling was slightly lower than

<table>
<thead>
<tr>
<th>Year</th>
<th>Dry sieve MWD (μm)</th>
<th>Decline (%)</th>
<th>Wet sieve MWD (μm)</th>
<th>Decline (%)</th>
<th>WSA &gt;500 μm Proportion of total (%)</th>
<th>Decline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>-R 607b</td>
<td>18.5</td>
<td>393b</td>
<td>13.4</td>
<td>11.4b</td>
<td>23.0</td>
</tr>
<tr>
<td></td>
<td>+R 745a</td>
<td></td>
<td>454a</td>
<td></td>
<td>14.8a</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>-R 635b</td>
<td>16.1</td>
<td>315b</td>
<td>10.0</td>
<td>8.9a</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>+R 757a</td>
<td></td>
<td>350a</td>
<td></td>
<td>9.2a</td>
<td></td>
</tr>
<tr>
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<td>-R 799b</td>
<td>13.2</td>
<td>382a</td>
<td>3.0</td>
<td>10.7a</td>
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<td>+R 920a</td>
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<td>395a</td>
<td></td>
<td>11.5a</td>
<td></td>
</tr>
</tbody>
</table>

* Means followed by the same letter within columns are not significantly different according to Duncan’s Multiple Range Test at \( p \leq 0.05 \).

b Decline in MWD = [(MWD of stubble returned treatments (+R) – MWD of stubble removed treatments (–R))/MWD of stubble returned treatments (+R)].
those at pre-sowing and increased from 0.185 m m$^{-1}$ at 0.1 m depth to 0.266 m m$^{-1}$ at 0.5 m depth. Again there was no significant difference in soil water content between the treatments.

At the pre-sowing measurement, the stubble removed treatment exceeded 2500 kPa from 0.13 to 0.33 m depth (Fig. 1a). Soil strength of the stubble removed treatment exceeded the soil strength on the stubble returned treatment by more than 600 kPa for much of this depth range. The stubble returned treatment remained significantly lower than the removed treatments and below the critical limit at all depths.

At the post-harvest sampling, high levels of soil strength had developed through the growing season in the shallow depth range (Fig. 1b). Soil strength on the stubble removed treatment exceeded 2500 kPa in the 0.04–0.07 m depth range, and again in the 0.13–0.25 m depth range. The stubble retained treatment remained significantly lower than the removed treatments and below the critical limit at all depths.

The legume systems also influenced soil strength but not to the same extent that stubble management did. Soil strength was generally lowest in the chickpea treatment below 0.1 m depth (data not presented). The highest penetration resistance of 2717 kPa was measured at the 0.15–0.20 m depth interval on the medic treatment following harvest. The lucerne treatment also had high soil strength values at depth.

4. Discussion

4.1. Soil structural properties

Soil pore size distribution, which determines rainfall entry, soil water retention and aeration, can be characterised by hydraulic conductivity measurements made at various tensions. Hydraulic conductivity was fastest in the pore sizes measured at 10 mm tension, and decreased as tension increased. Pore sizes which are measured at 10 and 20 mm tension (3.0 and 1.5 mm diameter, respectively) have been shown to be highly susceptible to collapse (Murphy et al., 1993). This was clearly shown in our study by the decrease in hydraulic conductivity of the cropped sites relative to the reference.

Declines in the hydraulic conductivity of the cropped sites relative to the reference sites were the result of the loss of continuous macropores connected to the soil surface and of declines in aggregate stability. Connolly and Freebairn (1996) surveyed a range of agriculturally important soils and found that the infiltration capacity of more than 80% of them declined with cultivation. They also reported that at least 3–5 year pasture phases were necessary to produce any lasting improvement in soil infiltration capacity.

Hydraulic conductivity was shown to be at least 65% greater on soils on which wheat stubble was retained after harvest. Stable soil aggregation and surface cover to prevent the slaking and sealing of the soil surface in response to rain drop impact, are factors responsible for improved infiltration and water content. Bissett and O’Leary (1996) found stubble retention and zero tillage produced 8-fold increases (from 12–33 to 145–206 mm h$^{-1}$) in saturated hydraulic conductivity relative to stubble removed and tilled soils. Chan and Heenan (1993) also showed the presence of more transmitting macropores (>1 mm) in a stubble retained direct drill farming system compared to a conventional farming system.
Hydraulic conductivity, to a large extent, is controlled by the amount of surface cover provided by plant material which prevents raindrop impact and soil surface crust formation. Improvements in the hydraulic conductivity over the 1995 growing season (Table 3) were largely lost after harvest when the wheat stubble was removed. Rose (1985) showed that mulching reduced the kinetic energy of rainfall and was effective in preventing crust formation. Hydraulic conductivity probably also increased throughout the growing season as plant roots improved soil structure by binding soil aggregates together and created biopores. Higher hydraulic conductivity probably accounted for the pre-sowing water content to 1 m increasing significantly from 0.25 m m\(^{-1}\) on the stubble removed treatments to 0.27 m m\(^{-1}\) on the stubble retained treatments (Whitbread et al., 2000).

The loss of soil aggregate structural stability are reflected in the 19, 16 and 13% declines in the DMWD of the bare soil treatments in 1993, 1994 and 1995, respectively, relative to the stubble retained treatments (Table 6). The stability of macroaggregates depends on the formation of bonding materials from SOM. These consist of transient bonding agents comprised of microbial and plant derived polysaccharides and temporary bonding agents derived from roots and fungal hyphae, especially mycorrhizal hyphae (Tisdall and Oades, 1982). The retention of crop residues not only protected the soil surface from raindrop impact, but provided organic materials as a precursor for aggregate formation.

By comparing aggregate size distributions between dry and wet sieved samples, the impact of water and energy from the sieving action can be seen on soil aggregates. Using this technique, there were no consistent differences between treatments of the field experiment. Aggregates were immersed prior to wet sieving (a very disruptive treatment) and this may have resulted in air entrapment within aggregates causing the aggregates to explode (Kemper and Rosenau, 1986). Although hydraulic conductivity was significantly increased with stubble retention, the increases in aggregate stability were not large enough to be detected using this method.

Cone penetrometer resistance is used to simulate the impedance encountered by growing roots. Reeves et al. (1984) reported penetration resistances of 2500 kPa on artificially compacted soils affected wheat plants resulting in stunted and chlorotic growth and reduced root growth.

The increase in soil strength due to two seasons of stubble removal was dramatic. Not only was cone penetrometer resistance on the stubble removed treatments significantly higher than the stubble retained treatments at all depths but it exceeded 2500 kPa, the critical limit where plant root growth is severely restricted (Taylor et al., 1966; Reeves et al., 1984), at intervals in the profile down to 0.3 m. This area is likely to contain a large proportion of the growing roots and lower soil strength is beneficial to root growth. There was a large increase in soil strength in the top 0.15 m during the growing season from the sampling prior to cultivation and sowing in May 1995, to the sampling following harvest in December 1995. Soil water at the first sampling was only slightly higher than after harvest so the increase in soil strength was a result of changes brought about by the growth of wheat. The magnitude and pattern of soil strength increases between the stubble removed and returned treatments were similar. Soil strength increased during the growing season probably due to wheat roots moving through the soil enmeshing fine particles of soil into aggregates (Haynes and Francis, 1993) and causing localised changes in pore water pressure due to drying of the soil through water uptake (Materechera et al., 1992). Increases in soil strength as a result of traffic have been widely reported (Soane, 1990), but traffic on these plots was minimal and only small machinery was used. The long term history of landuse is reflected in soil strength values at depth (below the current cultivation zone of 0.13 m), rather than the recent management practices.

### 4.2. Soil carbon

In this study the loss of soil C since clearing and cultivation has been substantial. Many studies have investigated the depletion of organic matter in cultivated soils by a comparison of organic matter and nutrient contents of a cultivated soil with those of a similar soil that has remained under permanent pasture or native vegetation (Tiessen et al., 1982; Dalal and Mayer, 1986). In a review of these studies, Tiessen et al. (1982) found that soils cultivated for grain lost about 1% of their organic C per year during the first 20–30 years of cultivation.
The aim of ley crop rotations in a cropping system is to improve soil nutrient levels and soil structure, to provide a disease break and to increase the yield of subsequent crops. This is achieved through N fixation, the decomposition of plant residues and the removal of host plants for insects and fungal disease. The concentration of total and labile C was significantly higher following the lucerne phase, however, there was no difference in either total or labile C of the chickpea, medic and fallow systems. The lucerne phase planted at least 3 years before the other legumes resulted in relatively small increases in total and labile C and the CMI when compared to the original levels of the reference sample. The effect of the legumes on soil C is limited due to the short phase in which the rotation was grown, the low plant material return and the high decomposition rates associated with these plant residues (Lefroy et al., 1995). Hossain et al. (1996) compared legume based wheat cropping systems using 2-year rotations of chickpea, lucerne and medic and a 4-year grass–legume ley phase. Total N and C increased significantly in the 0–10 cm soil layer only after the grass–legume ley due to longer accretion time and the larger residue input of fibrous grass roots. The short term nature and low residue inputs of many legume rotations, especially ones that are harvested or grazed, are unlikely to significantly benefit soil C levels.

The concentration of total and labile C increased by 7 and 13.5%, respectively, with the retention of the 1993 and 1994 wheat stubble. This resulted in an increase in the CMI from 16 to 18 (Table 2). At the time of sampling, only the 1993 wheat stubble had been incorporated so essentially the C differences between treatments were due to the retention and incorporation of the 1993 stubble. Although the analysis of the 1996 soil samples showed no increase in CT concentration, CL concentration significantly increased which resulted in an increase of the CMI from 19 to 26. In a sugarcane experiment in Brazil, increases of 39.7, 2.4 and 8.5% in CL, CNL and CT, respectively, were shown over a 12 month period of mulch return (Blair et al., 1995). The CL declines faster and is restored faster than CT or CNL and is hence a more sensitive indicator of the C dynamics of the system. Minimal increases in C concentrations over the 3 years of wheat stubble retention highlight the long timeframe associated with soil organic matter improvements.

The rate of decomposition of wheat stubble depends on the C:nutrient ratio, microbial accessibility to plant material and the temperature and water conditions. The wheat stubble remained on the soil surface during summer and were returned to the soil in May prior to planting. Decomposition prior to ploughing-in would have been mainly confined to roots and plant material laying in contact with the soil surface. The rain received over the summer period would have leached many of the nutrients from the straw, especially K. After the stubble was ploughed into the soil decomposition would have been rapid due to the warm and moist soil conditions favouring microbial growth as well as the process of cultivation breaking up straw and increasing surface area and microbial accessibility. Jenkinson and Ayanaba (1977) showed a similar decomposition pattern for labelled ryegrass between hot humid conditions in Nigeria and cool temperate conditions in England, but the whole decomposition process was four times faster in Nigeria. The rate of straw decomposition in the Australian wheat belt will therefore vary according to climatic variables.

A number of researchers have shown that crop residues become the precursors for aggregate formation. Golchin et al. (1994) separated free particulate organic matter on the basis of density (<1.6 mg m⁻³) and found it to be plant like in character. This solid substrate sustains a skin of decomposers that produces extracellular polysaccharides and metabolites which interact with the clay matrix. The particle of organic matter becomes the centre of an aggregate surrounded by a clay matrix held together by polysaccharide glues and may survive more than 50 years in soil (Oades, 1995). Waters and Oades (1991) demonstrated that SOM is protected from rapid decomposition by being inside aggregates. Macroaggregates (>250 μm) would result from the binding of microaggregates by transient or temporary organic matter such as roots and hyphae (Tisdall and Oades, 1982).

5. Conclusions

Substantial losses in soil fertility are evident by the comparison of an uncropped reference soil with soil that has been subject to long term cropping. Short term legume leys, which add highly decomposable plant materials to the system, were found to have no impact
on soil C and structure compared with a fallow. A longer term lucerne ley, however, resulted in some improvements in soil C concentrations. The improvement of soil physical properties measured in this study have been, to a large extent, due to ground cover provided by the crop residues as well as the provision of organic matter for aggregate formation and a source of nutrients and C for microbial activities. The improvement in soil structure was evident in higher hydraulic conductivities, larger aggregate size distribution and decreases in soil strength. The retention of stubble as groundcover over the summer rainfall period is especially important for preventing runoff and erosion processes in the northern cropping zone of Australia.

The dominating effect on soil C and structure in this study was found to be due to the return of wheat residues to the system. The increases in soil organic C concentrations, and the CMI, due to stubble retention were found to be relatively small and highlight the slow recovery of SOM, to levels where soil physical and chemical fertility may be adequate. Ley phases, which may include plant species with high biomass production and fibrous root systems, have the potential to accelerate this process, but are often an unviable proposition for land managers. Therefore farming systems which optimise the management of crop residues are likely to be more sustainable agricultural systems.

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