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Relating particulate organic matter-nitrogen (POM-N) and non-POM-N with pulse crop residues, residue management and cereal N uptake

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Abstract – Particulate organic matter nitrogen (POM-N) was evaluated as an indicator of crop residue source (pulse versus cereal) and residue management (no-tillage [NT], stubble burned [SB] or stubble mulched [SM]) on soil quality and subsequent crop productivity in a continuous cropping experiment in northern New South Wales (NSW), Australia. The relative contributions to POM of pulse versus cereal, and shoots versus roots, were studied using in situ 

15
N shoot labelling. Under NT, a greater proportion of organic N was found in POM-N > 250 µm (5.5% versus 3.5% [SM] and 2.7% [SB]) and POM-N > 53 µm (10.3% versus 9.7% [SM] and 8.7% [SB]). Pulse residues (particularly roots) contributed 2–7 times more N to POM and 2–4 times more N to non-POM-N than barley (15N data), but this increased contribution was not detectable with non-isotopic analysis. POM-N was sensitive to residue management, but was not a reliable measure of N inputs from pulse versus cereal residues, nor a useful tool for predicting subsequent crop N uptake.

pulse / cereal / crop residue / particulate organic matter / soil nitrogen

Résumé – Relation entre la matière organique azotée particulaire et non particulaire et les résidus de culture de légumineuses, leur gestion et le prélèvement d’azote par les céréales. La matière organique particulaire POM-N a été évaluée comme indicateur des sources des résidus de cultures (légumineuses ou céréales) et de la gestion des résidus (non-labour [NT], brûlage des pailles [SB], mulch de paille [SM]) sur la qualité du sol et la productivité induite des cultures dans une expérience continue de culture sans le Nord des New South Wales en Australie. Les contributions relatives des POM des légumineuses par rapport à celles des céréales et des tiges par rapport aux racines ont été étudiées en utilisant des tiges marquées à l’azote 15N in-situ. Sous NT, une plus grande proportion de l’azote organique a été trouvé dans la fraction POM-N > 250 µm (5,5 % par rapport à 3,5 % pour [SM] et 2,7 % pour [SB] et POM-N > 53 µm (10,3 % par rapport à 9,7 % pour [SM] et 8,7 % [SB]). Les résidus de légumineuses (particulièrement les racines) ont apporté 2 à 7 fois plus d’azote sous forme POM et 2 à 4 fois plus d’azote sous forme non particulaire que l’orge (données de 15N) mais cette contribution accrue n’était pas détectable avec une analyse non isotopique. POM-N était sensible à la gestion des résidus mais n’était pas un outil fiable pour les apports d’azote à partir des légumineuses comparativement aux résidus de céréales ni un outil utile pour prédire le prélèvement induit d’azote par la culture.

légumineuses / céréales / résidu de culture / matière organique particulaire / azote du sol

1. INTRODUCTION

Assessment of the labile, mineralisable fractions of soil organic matter (SOM) and freshly added residues, as well as soil total-N, could provide a deeper understanding of nitrogen (N) cycling within pulse-cereal systems than soil total-N alone [28, 34]. Labile SOM can be characterised by its biological performance (e.g. potentially mineralisable C or N), or may be measured as C and N concentrations of soil fractions separated by physiological (e.g. microbial biomass), chemical (e.g. partial oxidation by potassium permanganate), or physical means (e.g. particle or aggregate size or density). Of the latter, particulate organic matter (POM), where soil aggregates are dispersed then sieved to isolate...
non-complexed SOM, has recently been promoted as a promising index of land stewardship as it allows land managers to relate soil or agronomic management practices to consequences for soil quality [8, 37, 41].

Particulate organic matter (POM) is composed of partially or undecomposed plant residues, fungal hyphae, seeds, spores, faunal skeletons and humic material coating sand grains [6, 11, 20]. It has been shown to be closely linked to microbi ally-mediated processes in the soil and structural stability [2, 7, 18]. Vanlauwe et al. [34] demonstrated the lability of POM-N compared to N incorporated into other SOM fractions. Of the $^{15}$N derived from labelled leucaena ($Leucaena leucocephala$) residues added to field soils, the POM fraction (> 53 µm) contained about 70% of $^{15}$N remaining after 53 days of decomposition, but only 15% of that remaining after 2.4 years. Increasing POM in the soil resulted in increased soil microbial biomass, microbial activity and N mineralisation as the POM represents a readily digestible food source for microbes [42]. The importance of this fraction for mineral N supply was proven by strong correlations between POM-N derived from added residues, and maize ($Zea mays$) N uptake [34, 35]. The transient nature of POM compounds also inextricably links POM to the dynamics of soil macroaggregates [17, 31, 33] so that practices such as pasture leys and conservation tillage that enhance POM also benefit soil structure [8, 18, 31].

In 1981, NSW Agriculture commenced a research program in Australia’s northern grains region to assess the potential benefits of zero-tillage and residue retention in continuous cropping systems. During the 1990’s, the research was refocussed to include assessment of the winter pulses, chickpea ($Cicer arietinum$) and fababean ($Vicia faba$), and fertiliser N effects on wheat production. This change was in response to the need for higher levels of productivity and for environmentally-sustainable cropping in which soil nutrient resources were maintained, rather than depleted. Since 1995, we have examined the soils from this research program to investigate whether the effects of fallow (tillage and residue) management, crop rotation and N fertiliser on SOM have been positive, neutral or negative. We report results from a pulse-wheat rotation experiment to determine (i) the usefulness of POM as a sensitive measure of soil and agronomic management on soil quality, (ii) the relative contributions of shoot and root residues to POM-N and soil organic-N, and (iii) whether POM-N was related to N uptake by the following cereal crop.

2. MATERIALS AND METHODS

2.1. Experimental (main plots)

The fallow management/crop rotation experiment was conducted during 1981–99 near Breeza, northern New South Wales (NSW), Australia (31°5’S, 150°E) on a previously uncultivated, alkaline (pH 7.4–8.5 in 0.01M CaCl$_2$), black Vertisol (58% clay, 22% silt). Annual average rainfall at the site was 600 mm with a slight summer dominance. The experiment was a split-plot design arranged in randomised complete blocks. There were 3 main treatments (crop sequence), 3 sub-treatments (fallow management), 2 sub-sub-treatments (0 or 100 kg urea-N/ha added in 1993), and 4 replicates. The first crop sequence was continuous wheat ($Triticum aestivum$) with barley ($Hordeum vulgare$) in 1997; the second was wheat with 2 crops of grain sorghum ($Sorghum bicolor$) (1984/5, 1987/8) and 2 of chickpea (1993, 1997); the third was wheat with grain sorghum (1984/5), soybean ($Glycine max$) (1985/6), chickpea (1988) and 2 crops of fababean (1993, 1997). Fallow management treatments were no-tillage (NT), cultivated with stubble mulched (SM), and cultivated after stubble burned (SB). Fallow weeds were either controlled by herbicides (NT) or by 2–4 cultivations using tined implements (SM, SB). Plot size was 35 m × 10 m. Row spacings were 32 cm (cereals) or 64 cm (pulses). Pulses were inoculated just prior to sowing with the appropriate inoculant. Phosphorus plus zinc starter fertiliser was applied to all plots at sowing. Drought prevented winter cropping in 1982 and 1994. More comprehensive details of the site and cultural practices can be found in Felton et al. [16].

2.2. Sampling and analyses (main plots)

Shoot crop biomass was measured by hand harvesting two 1 m$^2$ quadrats in each plot after anthesis for wheat and barley and just prior to physiological maturity in the case of chickpea and fababean (peak biomass). Grain yield was measured by plot harvester from harvested areas of 30–40 m$^2$. Total N in finely-ground (< 0.5 mm) shoot and grain sub-samples was determined by Kjeldahl digestion.

The same shoot samples were used for natural $^{15}$N abundance assessments of chickpea and fababean N$_2$ fixation in 1993, with wheat as the non N$_2$-fixing reference. Kjeldahl digests were distilled and titrated, and the $\delta^{15}$N in acidified and concentrated distillates determined by isotope ratio mass spectrometry [3].

The $\delta^{15}$N values were expressed with reference to air N$_2$, thus:

$$\delta^{15}N = 1000 \frac{(R_{\text{sample}} - R_{\text{air}})}{R_{\text{air}}}$$  \hspace{1cm} (1)

where $R$ is the ratio mass 29/mass 28. The percentage of plant N derived from N$_2$ fixation ($%\text{Ndfa}$) was then determined using:

$$%\text{Ndfa} = 100(x-y)/(x-z)$$  \hspace{1cm} (2)

where $x$ is the $\delta^{15}$N of the wheat shoots deriving all of their N from the soil; $y$ is the $\delta^{15}$N of chickpea and fababean shoots; $z$ is the $\delta^{15}$N of chickpea and fababean shoots receiving all N from N$_2$ fixation. The values for $z$ were –1.65‰ (chickpea) and –0.50‰ (fababean) (M.B. Peoples, unpublished data).

Shoot N was the product of shoot biomass and N concentration (%N). Total crop N was then estimated by multiplying shoot N by a factor to account for below-ground N. Factor values, derived from $^{15}$N pot and microplot studies at the Breeza site, were 1.92 for chickpea, 1.37 for fababean and 1.59 for wheat [26]. Finally, total crop N fixed was calculated as:

$$\text{Crop N fixed (kg/ha)} = (%\text{Ndfa}/100) \times \text{crop N}$$  \hspace{1cm} (3)
In June 1995 (sowing), 5 soil cores per plot, and in 4 areas of adjoining virgin grassland, were taken, composited by depth (0–5, 5–10, 10–20 cm) weighed, mixed and sub-sampled. Sub-samples were either (a) kept field-moist, hand-sieved to < 8 mm, and stored at 4 °C for microbial biomass C (MBC) analysis [25], (b) air-dried and ground to < 2 mm for mineralisable nitrogen index (MNI) using anaerobic incubation at 40 °C for 7 days [6], and (c) air-dried and ground to < 0.2 mm for organic C (OC) [21], total N (TN) [13], and labile C (LC) [5] analyses. The POM was separated into two fractions, POM250 (> 250 µm) and POM53 (53–250 µm), then analysed for TN and OC as above.

Comparison of chemical measurements based solely on concentrations measured in a fixed sample depth ignores differences in soil mass caused by differing soil water content and cultivation treatments, particularly in swelling clay soils such as those at Breeze. Therefore, the quantities of measured properties were calculated in an equivalent soil mass based on 0–5 cm and 0–10 cm sample depths [15].

2.3. Experimental (microplots)

Full details of the 15N labelling field experiment are reported elsewhere [26]. Briefly, a month after sowing in 1997 (seedling stage), 4 metal-frame microplots (0.64 m length × 0.5 m width × 0.5 m length) were inserted to a depth of 0.3 m in the soil of each NT main plot of fababean (cv. Fiord), chickpea (cv. Amphithyst) and barley (cv. Kaputah). Each microplot contained either 7 (chickpea), 8 (fababean), or 20 (barley) plants. Each microplot plant was shoot-fed 0.2 mL of 0.5% 15N urea (98 atom% 15N excess) 5 times during vegetative and early reproductive growth using leaf-flap (fababean), petiole (chickpea) or cut leaf-tip techniques [27]. Microplot 1 was destructively sampled and not used for further studies. Following harvest, the 15N-labelled and unlabelled plant residues were returned to microplots 2–5 in the following combinations:

Microplot 2 – 15N shoot/14N root
Microplot 3 – 14N shoot/15N root
Microplot 4 – nil shoot/15N root
Microplot 5* – 15N shoot/14N root
* new microplot

The 15N-labelled shoot residues from microplot 3 were returned to the soil surface of microplot 5, and equivalent amounts of unlabelled shoot residues placed in microplot 3. All microplots were covered with 13-mm diameter wire-mesh to restrict loss of surface-applied residues during the summer fallow. In June 1998, all microplots were sown with wheat (cv. Janz).

2.4. Sampling and analyses (microplots)

Microplots 1 were sampled during grain-filling (October 1997) to quantify below-ground N (BGN) on the basis of the total N and 15N contents of the shoots, recovered root fragments, and microplot soil (all soil collected to 25 cm depth, cored 25–45 cm) as described by Russell and Fillery [30]. Fababean, chickpea and barley grain was harvested at crop maturity (December 1997) from each of the remaining 3 microplots.

In June 1998 (wheat sowing), 2 soil cores (0–100 cm) per plot, one in the original plant row and the other between the rows, were taken from microplots 2, 3 and 5 and from an area just outside the micro-plots (for natural 15N abundance estimates). The cores were then segmented by depth (0–5, 5–25, 25–50 and 50–100 cm), composited, and subsampled. In December 1998, wheat was harvested from all microplots and main plots. Grain was threshed manually and dry weights, %N and 15N determined for both grain and straw. Soil cores (0–50 cm) were taken from each micro-plot and main plots as described for June 1998.

Shoots, roots, fallen leaves, grain, whole soils and POM (POM250 and POM53 combined) separates were air-dried then ground to < 0.1 mm for analysis of total C, TN and 15N enrichment by combustion using an automatic N and C analyser interfaced with a 20-20 stable isotope mass spectrometer (Europa Scientific, Crewe United Kingdom).

2.5. Statistical analysis

Soil and plant results from 1995 were statistically analysed by analysis of variance (ANOVA) using a split plot design with crop sequence as main plots, fallow management as sub-plots and fertiliser addition as sub-sub plots. The 1998 soil results were analysed by ANOVA using a split-plot design with crop sequence as main plots and microplots as sub-plots. Correlations were used to examine the relationships between soil N fractions and other indices of labile organic matter. Simple linear regression with groups (crop sequence) was used to investigate the amount of increase in 1995 crop productivity associated with increasing levels of soil N fractions measured at sowing. All statistical techniques were performed with Genstat 5.4.1 4th ed. (1998).

3. RESULTS

3.1. Main plots (1981–95)

Under NT, SOM was concentrated at the soil surface (0–5 cm) (Fig. 1). Levels were similar to those in the SM plots at 5–10 cm, and were slightly less than SM and SB at 10–20 cm. Since the major influence of management practice was clearly at the soil surface, the remainder of this paper deals primarily with the 0–5 cm surface layer.

Despite the decreased water erosion and increased water infiltration and storage observed under NT, crop production (mean wheat yield) during 1981–1993, was greater under SB (2.90 t/ha) than NT (2.54 t/ha) or SM (2.51 t/ha) (individual data not shown, see Felton et al. [16]). Crop yields were probably affected by N immobilisation by cereal straw during the summer fallows (NT > SM > SB) and stubble-borne disease carry-over (NT = SM > SB). Therefore, crop residue retention and placement, rather than crop productivity, had the dominant influence on surface soil organic N.
A range of crop residue quantities and qualities, determined by differences in C/N ratio, were generated by the 1993 crops (Tab. I). Estimated ranges for residue-N were 26–230 kg N/ha, and were 20–178 for C/N. The chickpea crop produced much more crop N than either fababean or wheat, although similar amounts of N were removed in the grain of all three crops. This resulted in chickpea leaving more N in residues compared to fababean and wheat, particularly in NT plots. The chickpea residues were highly enriched in N compared to the other crops, with an average C/N ratio of 23, compared to 38 for fababean, 115 for unfertilised wheat and 57 for N fertilised wheat. C/N ratio is a well-established indicator of likely residue decomposition rate.

Fourteen years of continuous winter crop/summer fallow substantially reduced N in both POM and non-POM fractions (0–5 cm equivalent soil mass) compared to the adjacent virgin native grassland (Tab. II), with the more labile POM...
fractions most affected. The N loss from all fractions was greater under SB than NT, with SM intermediate. POM250-N was reduced by 49% (NT) to 82% (SB), POM53-N by 44% (NT) to 66% (SB), and non-POM by 32% (NT) to 46% (SB).

Loss of C from the three fractions followed similar patterns (data not shown), but there was a tendency for a greater proportion of C loss from the POM fractions than that of N, and the reverse in the non-POM, i.e. more N was lost than C in non-POM under cultivation. The proportion of SOM-N made up by POM250-N ranged from 2.7% (SB) to 5.5% (NT), compared to 7.6% under virgin grassland. For POM53-N, the range was 8.7% (SB) to 10.3% (NT), compared to 13.1% under virgin grassland.

There were few significant effects of prior crop or N fertiliser application on the soil organic N fractions (Tab. II). After the 1993 wheat, there was more N and C in the POM53 fraction and more C in the non-POM fraction, and consequently the whole SOM, than after fababean or chickpea (C data not shown). C/N ratios in the POM250 and non-POM fractions were decreased after legume crops compared to the

<table>
<thead>
<tr>
<th>Fallow treatment</th>
<th>N fert. (1993) (kg N/ha)</th>
<th>Nitrogen (kg N/ha) POM250^D POM53^E non-POM^F Total</th>
<th>C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>after fababean (1993)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>0</td>
<td>35 55 499 683 13.3 15.1 9.4 9.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>42 75 497 722 13.2 11.4 9.7 9.4</td>
<td></td>
</tr>
<tr>
<td>SB</td>
<td>0</td>
<td>15 44 382 515 14.3 12.2 11.1 10.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>16 45 407 507 12.4 11.6 10.5 10.2</td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td>0</td>
<td>21 53 416 548 11.5 11.2 10.5 9.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>20 51 416 541 12.4 11.3 10.1 10.0</td>
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<tr>
<td>after chickpea (1993)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT^A</td>
<td>0</td>
<td>42 73 466 695 13.9 12.6 10.0 9.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>35 73 483 695 13.4 11.7 9.9 9.5</td>
<td></td>
</tr>
<tr>
<td>SB^B</td>
<td>0</td>
<td>14 43 371 503 12.5 13.2 11.3 9.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>15 47 396 496 12.7 12.1 10.5 10.4</td>
<td></td>
</tr>
<tr>
<td>SM^C</td>
<td>0</td>
<td>15 50 403 531 15.7 12.3 10.6 9.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>17 46 387 531 13.5 12.1 10.7 9.9</td>
<td></td>
</tr>
<tr>
<td>after wheat (1993)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>0</td>
<td>38 79 494 709 13.9 11.2 10.1 9.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>40 80 468 719 14.1 12.4 11.2 9.6</td>
<td></td>
</tr>
<tr>
<td>SB</td>
<td>0</td>
<td>12 44 364 502 14.5 13.3 12.7 10.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>12 40 390 503 15.9 13.0 11.1 10.3</td>
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<tr>
<td>SM</td>
<td>0</td>
<td>18 54 415 556 13.0 12.5 11.9 10.0</td>
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<tr>
<td></td>
<td>100</td>
<td>22 64 410 587 13.1 12.0 11.3 9.6</td>
<td></td>
</tr>
</tbody>
</table>

Significance^G (*** P < 0.01, ** P < 0.05, * P < 0.10, n.s. not significant P > 0.10)
- crop n.s. ** n.s. * n.s. * n.s.
- fallow *** *** *** n.s. n.s. *** ***
- fertiliser n.s. n.s. n.s. n.s. n.s. * * n.s.

Standard errors (differences)
- crop – 2.0 – – 0.4 – 0.4 –
- fallow 2.6 3.3 8.6 10.0 – – 0.3 0.1
- fertiliser – – – – 0.3 0.2 –

Virgin native grassland

- – 75 130 711 989 14.8 13.1 9.2 9.9

[^A]: Stubble retained, no-tillage.
[^B]: Stubble burnt then cultivated.
[^C]: Stubble retained then cultivated (mulched).
[^D]: POM250 = particulate organic matter > 250 μm.
[^E]: POM53 = particulate organic matter 53–250 μm.
[^F]: Non-POM = organic matter < 53 μm.
[^G]: Significant interactions are detailed in text.
continuous wheat sequence. The application of N fertiliser to the 1993 crop increased POM53-N in NT plots and non-POM-N in SB plots. N fertiliser also led to decreased C/N ratios in SOM after wheat, and in non-POM where stubble was burned during the fallow.

The relative lability of the POM and non-POM soil N fractions was demonstrated by highly significant correlations with other measures of labile SOM (Tab. III). In both 0–5 cm and 5–10 cm samples, POM250-N was more highly correlated with the microbial biomass, mineralisable N and labile C indices than POM53-N and non-POM-N. However, total N and POM250-N were also closely correlated (r = 0.93).

### 3.2. POM-N dynamics – microplots 1997–98

Although there were no significant prior (1997) crop effects on soil POM-N and non-POM-N quantities in the 1998 sampling (data not shown), the microplot 15N data showed significant effects of crop type and plant part (i.e. shoot versus root) on the isotopic composition of POM-N and non-POM-N (Tab. IV). Enrichments of POM-N were generally higher than for non-POM-N, but with similar trends. Generally, %POM-N and non-POM-N derived from residues were highest for fababean, followed by chickpea then barley. After the winter cropping season, about 45% less 15N was recovered in the POM fraction after fababean, compared with the previous (June) sampling, suggesting substantial N mineralisation, immobilisation (non-POM increased in 15N over the same period), or N loss. With the other two species, the proportions of 15N in the POM fraction were almost identical for the June and December samplings. Enrichments for all species were highest in microplots 2 (15N-labelled shoots and roots), followed by microplots 3 (15N-labelled roots), then 5 (15N-labelled shoots). Thus, in the case of fababean, 65% of the residue-derived N in the POM had come from roots, with 35% from shoots. In contrast, barley and chickpea roots contributed 80–90% of the residue-derived N found in POM. Similar trends of above-ground/below-ground contributions were seen in the samples collected in December 1998. There was up to 7 times more POM-N and TN derived from 15N-labelled residues found in the surface-soil (0–5 cm) compared to the sub-surface soil (5–25 cm) (data not shown), particularly in microplots 5 where the only 15N-labelled residues were shoots applied to the soil surface.

In terms of the overall fate of the 1997 crop residues, a large proportion (40–60%) of fababean residue-N was found

### Table III. Correlations (r) between soil total N, soil N fractions, and other measures and indices of labile organic matter in 0–5 cm and 5–10 cm samples taken from main plots in 1995.

<table>
<thead>
<tr>
<th></th>
<th>POM250-N</th>
<th>POM53-N</th>
<th>Non-POM-N</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0–5 cm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBC</td>
<td>0.93 ***</td>
<td>0.81 ***</td>
<td>0.78 ***</td>
<td>0.96 ***</td>
</tr>
<tr>
<td>MBC/OC</td>
<td>0.90 ***</td>
<td>0.80 ***</td>
<td>0.76 ***</td>
<td>0.92 ***</td>
</tr>
<tr>
<td>MNI</td>
<td>0.91 ***</td>
<td>0.78 ***</td>
<td>0.79 ***</td>
<td>0.94 ***</td>
</tr>
<tr>
<td>MNI/TN</td>
<td>0.79 ***</td>
<td>0.69 ***</td>
<td>0.68 ***</td>
<td>0.79 ***</td>
</tr>
<tr>
<td>LC</td>
<td>0.87 ***</td>
<td>0.76 ***</td>
<td>0.72 ***</td>
<td>0.91 ***</td>
</tr>
<tr>
<td>LC/OC</td>
<td>0.68 ***</td>
<td>0.60 ***</td>
<td>0.58 ***</td>
<td>0.72 ***</td>
</tr>
<tr>
<td><strong>5–10 cm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBC</td>
<td>0.56 ***</td>
<td>0.38 **</td>
<td>0.27 *</td>
<td>0.55 ***</td>
</tr>
<tr>
<td>MBC/OC</td>
<td>0.34 **</td>
<td>0.24 *</td>
<td>0.09</td>
<td>0.27 *</td>
</tr>
<tr>
<td>MNI</td>
<td>0.62 ***</td>
<td>0.38 **</td>
<td>0.39 ***</td>
<td>0.68 ***</td>
</tr>
<tr>
<td>MNI/TN</td>
<td>0.34 **</td>
<td>0.28 *</td>
<td>0.03</td>
<td>0.25 *</td>
</tr>
<tr>
<td>LC</td>
<td>0.72 ***</td>
<td>0.35 **</td>
<td>0.53 ***</td>
<td>0.83 ***</td>
</tr>
<tr>
<td>LC/OC</td>
<td>0.58 ***</td>
<td>0.19</td>
<td>0.44 ***</td>
<td>0.66 ***</td>
</tr>
</tbody>
</table>

POM250-N = particulate organic matter nitrogen> 250 μm.
POM53-N = particulate organic matter nitrogen 53–250 μm.
Non-POM-N = organic matter-nitrogen < 53 μm.
TN = total soil nitrogen.
MBC = microbial biomass carbon.
OC = organic carbon.
MNI = mineralisable nitrogen index.
LC = labile carbon (permanganate oxidation method).
*** P < 0.001, ** P < 0.01, * P < 0.05.
in POM (June 1998), with only about 10% in the mineral-N pool [26]. By the time of wheat harvest in December 1998, 26% remained in POM, with 51% in non-POM. On the other hand, most chickpea residues were found in the non-POM fraction (30–70%), with only 7–13% in POM and about 10% as mineral N. Barley was more similar to chickpea than fababean, although less of the residues of barley ended up as mineral N (0–6%). It was not possible to trace the POM-15N into the following wheat crop as there was already much 15N present in the mineral N pool. Only the POM-N (and non-POM-N) found after fababean was likely to have contributed to wheat N.


All soil organic N fractions, measured in June 1995 (sowing), were weakly related to the measures of the 1995 crop production, viz. biomass, biomass N, grain yield and grain N yield (Tab. V). However, non-POM-N (and total N) following pulses was better correlated with the 1995 wheat production than POM-N fractions. This infers that N mineralised from non-labile SOM during the crop growing season (in-crop) was beneficial to the growth and N uptake of the 1995 wheat crop. However, 1995 wheat production should not have been sensitive to in-crop N mineralisation as more than 180 kg nitrate-N/ha to 1.2 m (measured at sowing) had accumulated from mineralisation during the previous 18-month fallow-drought-fallow. On the other hand, productivity of wheat following wheat was not related to non-POM-N (or total N). The interaction of non-POM-N and crop N uptake is shown in Figure 2. Increasing non-labile soil N benefited wheat grown after the pulses, but had no effect on wheat after wheat. The latter may be due to cereal disease in monoculture wheat.

The 1997 crop significantly affected dry matter and grain yield of the 1998 wheat crop. Grain yield of wheat after fababean was 2.3 t/ha, after chickpea was 1.9 t/ha, and after barley was 1.4 t/ha. [26]. While the 15N in the POM fraction (measured in June 1998) explained 32% of variation in wheat grain yield and dry matter, mineral N to 1.2 m (measured at sowing) was a much better predictor of wheat productivity.
explaining 68% of variation in dry matter production and 62% of variation in grain yields.

4. DISCUSSION

4.1. POM-N dynamics

We found POM, particularly the POM250 fraction, comprising macroorganic matter and soil litter, to be highly correlated with soil biological properties such as microbial biomass and N mineralisation potential, suggesting a key role for this SOM fraction as a substrate and source of nutrients for soil microbial activity. The in situ $^{15}$N-labelling of chickpea, fababean and barley showed clearly that root residues contributed much more to POM (65–90%) than shoot residues (10–35%). Similarly, other researchers have used in situ $^{13}$C and $^{14}$C-labelling both in glasshouse and field studies to demonstrate that root residues of oats (*Avena sativa*) [17] and hairy vetch (*Vicia villosa*) [29] contributed substantially more to POM than shoot residues, and also that root-derived POM was more important in the formation of stable macroaggregates [18, 38]. It follows that, for a given level of above-ground residue inputs, plants that contribute more to
root production will have greater benefit to POM, soil structural stability, and possibly SOM. For example, root production under grass-based pasture on a Vertisol in southern Queensland, Australia (10 t DM/ha/year), increased SOM compared to continuous cereal cropping (2 t DM/ha/year); both pasture and cropping systems had similar above-ground residue inputs (2.5 t residues/ha.year) [14]. In northwestern NSW, Australia, Chan [8] found that almost 70% of the increase in organic C in a Vertisol under pasture could be attributed to the increase in POM-C.

Our in situ 15N-labelling also showed that plant species were quite different in their contributions to POM-N. Pulse residues contributed 2–7 times more N to POM and 2–4 times more N to non-POM-N than barley. That we could not demonstrate any statistically-significant prior crop effects on the unlabelled 1998 POM-N may be the result of the necessarily limited number of cores (2) taken from each microplot and the spatial heterogeneity of residues and SOM. The effects of prior (1993) crop on 1995 POM-N were statistically-significant, with a decrease after pulse crops, relative to wheat. This trend would be the result of the 18-month fallow period (because of 1994 drought) between prior crop harvest and the 1995 POM measurements. During the fallow, there appeared to be greater decomposition of the more highly-decomposable pulse residues, as indicated by the lower C/N ratios (Tab. I). The 15N data also indicated substantial turnover of fababean-derived POM during the winter cropping season (Tab. IV).

4.2. Soil and crop management and POM

POM has been shown to be a sensitive indicator of management effects on soils. Examples include changing land use from grassland/pasture to cropping and vice versa [8, 12, 32], and frequency of cultivation [7, 23, 31]. Our results demonstrated POM to be more sensitive to change from native grass-based pasture to continuous winter cropping than non-POM and SOM (Tab. II). Dalal and Mayer [12] and Chan [8] also found that POM was preferentially lost from SOM in Vertisols when native vegetated areas were first used for cropping. POM in our study was also more sensitive to crop residue retention and placement (tillage versus no tillage) than non-POM (Tab. II).

We also explored short-term effects on POM and other SOM fractions of prior crop and fertiliser N. In other studies, POM was not particularly responsive to prior crop. For example, Hulugalle and Entwistle [22] found more POM-C in the soil after cotton (Gossypium hirsutum) than after cowpea (Vigna unguiculata) or a bare fallow, but the reverse effect in the non-POM-C. Willson et al. [41] found that POM did not reflect differences in N mineralisation potential of soil with recently-incorporated residues of maize, soybean and wheat. Lentil (Lens culinaris)-wheat rotations had a negative effect on light fraction OM (a similar fraction to POM) in a study by Biederbeck et al. [4], compared to continuous wheat, flax (Linum usitatissimum)-wheat or canola (Brassica napus)-wheat rotations. In our study, rotation of wheat with either fababean or chickpea either had no effect (1998 results – NT only) or led to less POM53-N, POM53-C, non-POM-C and total C compared with a continuous wheat rotation (Tab. II). Our results therefore concur with the general trend of either no response or a decline in POM after pulses.

Fertiliser N has been shown to increase light fraction SOM only when crop residue inputs were increased through higher crop productivity [4]. The application of N fertiliser at sowing in 1993 had no effect on pulse crop production, other than to reduce the pulse’s reliance on N2-fixation, but significantly increased wheat biomass, biomass N, grain, and grain N, residue N and decreased crop residue C/N ratios (Tab. I). Of the 1995 soil measurements, only decreases in C/N ratio of SOM and non-POM (SB plots) reflected these effects.

Therefore, POM can change as a result of changes to crop residue quantity, quality (decomposability), placement within the soil (decomposition rate), or any combination of these factors. It should be possible to stabilise or even slowly increase SOM under continuous cropping by maximising crop productivity through crop rotations (particularly pulses), judicious fertiliser management, and conservation farming practices. In a US study, Varvel [36] found that both crop rotation and N fertiliser significantly increased total soil C and N, even under conventional cultivation practices. Dalal and Chan [11], in reviewing SOM research in rainfed cereal cropping systems of Australia, found mixed evidence of these practices (examined separately) enhancing SOM-C, but found few studies where these practices were combined.

4.3. POM as an indicator of potential crop productivity

Yakovchenko et al. [42] cautioned against linking POM in soil to crop productivity as the amount of N mineralised from POM was generally small compared to crop N demand. In contrast, Vanlauwe et al. [34, 35] found that POM-N from the addition of legume residues contributed significantly to subsequent cereal N uptake. However, their soil had much less potential for N supply from non-POM N reserves than reported here. Also, in their study, the demand for available N from their cereal test crop was only a quarter of the cereal N demand in our study, so the N supply from POM-N reserves was sufficient to meet crop demand. In our study, POM-N was either weakly related or not related to the productivity of the following crop. Where it was related (Tab. IV), it was generally found to be a weaker relationship than that of non-POM-N and crop productivity. These results suggest that the demonstrated beneficial effects of increased POM on soil structural integrity [2, 8, 18, 33] had less influence on crop productivity than other factors, such as plant N supply. The Vertisol studied here is one of the dominant cropping soils in the northern NSW grains region of Australia [39], and contains substantial amounts (> 50%) of swelling and cracking clays. In these soils, SOM is less important for structural integrity, cation-holding capacity, water-holding capacity, and pH buffering than clay content, clay type, electrolyte concentration, and exchangeable sodium content [10].

The N not accounted for in the inorganic and POM fractions is likely to be residue organic N present in humus (clay
and silt-stabilised SOM), which will be more slowly available for mineralisation. That the non-POM was a better source of in-crop N supply seems to be at odds with the notion of POM being closely linked with N mineralisation potential. However, decomposition studies of separated soil particle-size fractions (reviewed by Christensen [9]) and studies where POM (or light fraction SOM) has been added as an amendment to incubated soils [1, 40, 42] all tended to show that, while POM was an important source of biologically-active C for microbes, it was neither an immediate nor major source of mineral N. Although POM (and light fraction SOM) appears to mineralise C more quickly than non-POM, net N mineralisation from the POM is often less than from the non-POM. In fact, Whalen et al. [40] showed that the light fraction was more of a sink for mineral N, regardless of land management. This apparent contradiction is thought to be because the higher C/N ratio in POM than non-POM leads to N immobilisation by the microbes feeding on the POM [9]. In our study, the C/N ratio of POM250 (13.5) was greater than that of POM53 (12.3) and that of non-POM (10.7). Yakovchenko et al. [42] also found that fine POM (< 250 μm) was more decomposed (had a lower C/N ratio and lower C mineralisation rate). Our 1995 results also indicated that C/N ratio of POM250 (and the non-POM) was affected by the source of recently-added residues, with higher C/N after wheat (14.1) than after chickpea (13.6) or fababean (12.8) (Tab. 1). A similar, though not statistically significant, trend was found in the June 1998 POM(all) results where C/N ratios were 11.8 (fababean), 12.1 (barley) 12.4 (chickpea). The effects of these trends in C/N ratio may be apparent in the greater in-crop mineralisation of fababean-derived POM-N compared to either chickpea- or barley-derived POM-N.

4.4. POM as an indicator of soil quality

POM has several attributes that make it suitable as an indicator for relating soil or agronomic management practices to consequences for soil quality. These attributes include a rapid half-life and positive correlations with the biologically-active SOM fractions, N mineralisation and soil aggregation [37]. Chan [8] suggested that it may be possible to monitor POM simply by dispersion, sieving and weighing, without the need to determine organic C or N concentrations. This simplicity would give it greater potential for direct use by land managers. However, farmers will only monitor the impacts of changing soil or agronomic management on soil quality if the measurements can be related to yields and short-term profitability [24], not long-term ideals such as sustainability [37]. Dalal and Chan [11] concluded that while the general benefits of SOM to agricultural soils in Australia were well-known, there was limited information on the effects of increasing SOM, and specific fractions such as POM, on soils and agricultural sustainability in the Australian cereal belt.

Our study found no strong relationship between POM-N and productivity of a following cereal crop. This is not to say that no such relationship exists. Crop response to soil quality is difficult to separate from yield response to management and climate [19]. Furthermore, it may be that crop productivity only responds to POM (and SOM in general) below a threshold and that above it there is no further response to change [24]. Clearly, if this is the case, the soil under study has not reached such a threshold. It should be noted that neither the 1995 (after an extended fallow due to 1994 drought) nor 1998 (record winter season rainfall and flooding) wheat crops were grown under conditions considered representative of the region. We feel that these limitations on the data justify further analysis of POM in other long-term field experiments where crop rotation and N fertiliser addition treatments were more consistently applied over time.

5. CONCLUSIONS

We have demonstrated, using 15N as a tracer, that pulse crop residues (particularly roots) contributed much more to POM-N and non-POM-N than a cereal crop, but this increased contribution could not be detected using normal (non-isotopic) field sampling and analysis. Instead, the 1995 data showed a decline in POM53 and non-POM-C, and a decrease in C/N ratio of POM250 and non-POM after the 1993 pulses. These changes indicate greater decomposability of soil organic matter after pulse crop residues – a desirable characteristic in terms of mineral N supply for short-term productivity but undesirable in terms of longer-term SOM maintenance. Analysis of the relationships between soil N fractions and crop productivity showed that, while the POM after pulses may decompose more quickly, it was likely that much of the N released was immobilised by the soil biomass and so was not of direct benefit to the growing crop. Neither was any impact evident of increased POM on soil structural integrity beneficial to crop productivity in this self-mulching Vertisol. In fact, non-POM-N was better related (though not strongly) to crop productivity. Therefore, although we have reconfirmed that POM is a labile SOM fraction sensitive to major changes in residue management practices and intimately related with important biological processes, POM, measured at sowing, was not a useful tool for predicting subsequent crop production or crop N uptake.

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Pulse crops, residue management and POM-N


