Characterising the soil organic carbon and nitrogen pools and the mineralisable soil nitrogen at MPfN field trial sites

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Summary

Despite the wide variety of plant residues cycling through the agricultural systems studied in the MPfN Program, it is shown that linear regression equations can be used to describe the following relationships:

- *total organic carbon with total organic nitrogen;*
- *particulate organic carbon with total organic C;*
- *particulate organic C with particulate organic N; and*
- *$PMN_{7\ day}$ with $PMN_{14\ day}$.*

These equations are applicable across the agricultural systems, soils and environments of the MPfN Program and provide simple algorithms that can be used to inform modelling of soil N and C pools.

For the agricultural systems studied in the MPfN Program:

- *field crops (cotton and sugarcane) and tropical tree crops (mango) had the lowest potentially mineralisable N (PMN_{14day}), followed by temperate tree crops (cherry). Dairy pastures ranging from sub-tropical to temperate climates had the highest PMN_{14day}.*
- *short term (7 day) N mineralisation (PMN_{7day}) was best correlated with particulate organic C, while steady state mineralisation (PMN_{14day} minus PMN_{7day}) was best correlated with particulate organic N.*
- *if particulate organic matter measurements are not available, then total organic C is the best indicator of short term mineralisation and total organic N is the best indicator of steady-state N mineralisation.*

The PMN values were obtained on soil samples submitted by the individual projects from nil applied N treatments. For each agricultural system, these results can therefore be calibrated against crop N uptake from the nil applied N treatments using appropriate modifiers for the effects of soil moisture and soil temperature on in-season soil N mineralisation.

Progressive carbon dioxide evolutions from 0-7 days and 7-14 days were measured on six cotton soils and two selected sugarcane soils to assess the relationship of soil respiration with labile organic C and with PMN. While the NSW cotton soils showed similar levels of respiration per unit labile organic carbon as the Qld cotton and sugarcane soils, this was associated with net nitrogen immobilisation or low PMN because of low initial soil mineral N compared to the other soils. Understanding the reasons for the different initial soil mineral N levels in the cotton soils will assist in predicting whether net mineralisation or net immobilisation is likely in this cropping system.

Dairy sites in Victoria and northern NSW, orchards in Tasmania, mangos in NT and sugarcane in Qld showed large coefficients of variation in ratios of labile C/total organic C and/or labile C/particulate organic C. This variation indicates that management affects the C lability in these systems and warrants further investigation to identify the management practices that support high levels of labile soil C.

Background

The MPfN Program covers a wide range of agricultural systems, environments and soil types, and the focus of the program is on improving N use efficiency. The large geographical spread of projects provides an opportunity to benchmark the soil N mineralisation potential of agricultural soils under different management systems, and also to benchmark the lability of the soil organic carbon and soil organic nitrogen pool in these soils. The diverse cropping/pasture systems being studied in the MPfN Program provide crop /pasture residues (above-ground components and roots) of different C and N composition and quantity, and this may result in different soil C stocks and rates of soil N mineralisation.

The aim of this study was to undertake the following soil analyses: potentially mineralisable N (PMN); particulate organic C (POC) and N (PON); and permanganate oxidisable (labile) organic C (POxC) on surface soil samples from each MPfN project.

Because the PMN analyses indicated that some cotton soils exhibited net immobilisation rather than net mineralisation, further analyses (carbon dioxide evolution as a measure of microbial activity) were subsequently undertaken on a subset of cotton and sugarcane soils.

The results are used to benchmark PMN, POC, PON and POxC across regions/soil types/agricultural systems. Relationships between PMN and the various measures of soil C and N were used to assess whether there are differences in the quality (lability) of soil organic matter associated with the different agricultural systems. In addition, soil respiration per unit of total /labile organic C was calculated for the subset of cotton and sugarcane soils to identify whether there were any intrinsic soil organic matter characteristics of these soils that might impact microbial activity and therefore mineralisation of soil organic matter.

Because PMN analyses were carried out on soil samples from the nil applied N treatments of the MPfN projects, results will assist individual projects to relate the crop N uptake from the nil applied N treatment in the field to PMN. This will allow assessment of the effects of seasonal conditions (particularly soil temperature and soil moisture content) on the in-season soil N mineralisation of that agricultural system.

Figure 1 indicates how PMN, soil organic C and organic N analyses interact to inform modelling of in-season soil N mineralisation (which is a crucial component of N budgeting), and NUE indicators for the different farming systems in the MPfN program.

Methods

Soils

Each project provided surface soil samples from each rep of the nil N treatment at each field site. Site details and sample depth are provided in Table 1. All soils were dried (40^0C) and passed through a 2mm sieve. For analysis of total organic carbon, samples were ground <0.5mm.

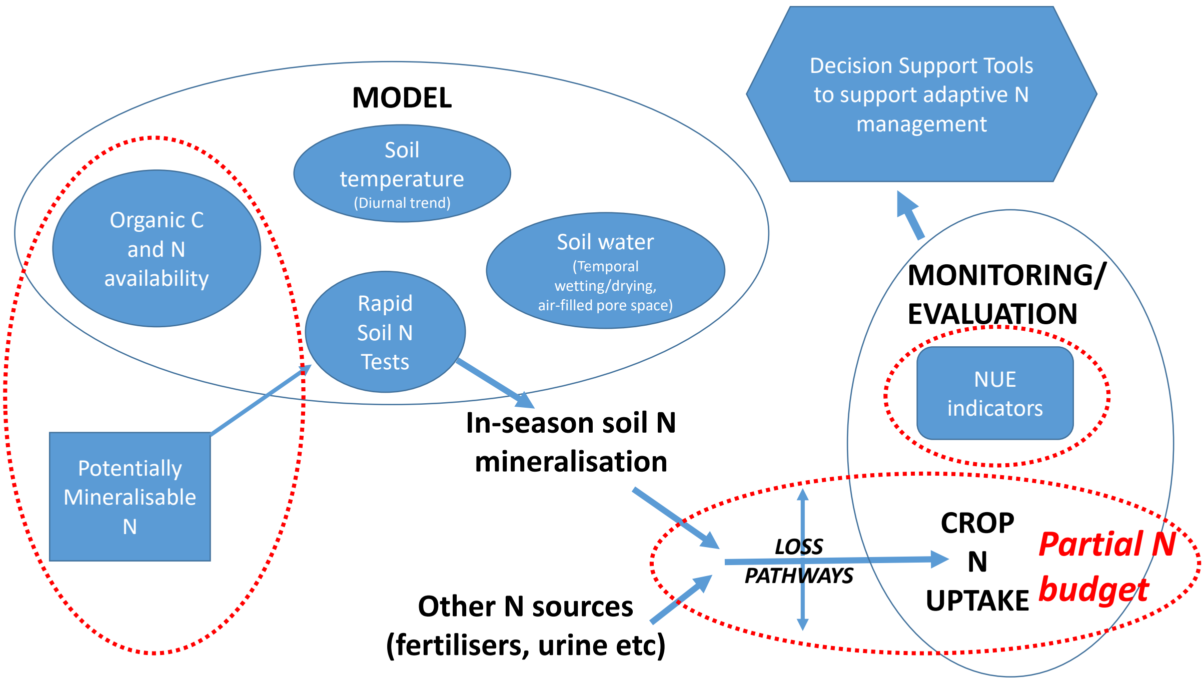


Figure 1. Components of the N cycle and inputs required for the development of models and M&E tools to inform decision support frameworks for the efficient use of N.

Analyses

The following analyses were carried out according to the following Rayment and Lyons (2016) method codes:

pH(1:5 water): Method 4A1

EC(1:5 water): Method 3A1

Total organic C (TOC): Method 6B3 (Dumas high temperature combustion, infra-red/thermal conductivity detection with prior chemical removal of carbonates)

Total organic N (TN): Method 7A5 (Dumas high temperature combustion)

Particulate organic C (POC): Method 6C1 for organic carbon analysis determined on the >53um fraction of chemically dispersed <0.5mm bulk soil sample

Particulate organic N (PON): Method 7A2b for organic N analysis carried out on the >53um fraction of chemically dispersed <0.5mm bulk soil sample

Permanganate oxidisable C (POxC): Method 6E1 (33mM potassium permanganate oxidisable C)

Potentially mineralisable N at 7 days (PMN_{7day}) and 14 days (PMN_{14day}): Method 7D1b

Carbon dioxide evolution: PMN containers were capped on Day 0 and the headspace sampled for CO_2 analysis by gas chromatography prior to destructive sampling for soil mineral N of the 7 day containers. For the containers being taken through to 14 days, caps were replaced after flushing with air. At 14 days, the headspace was sampled and soil extracted for mineral N as described for the 7 day containers.

Results

Analytical results are presented in Table 1.

pH and EC

Soil pH(1:5 water) ranged from strongly acidic to strongly alkaline, with sodic surface soils at the cotton sites in Queensland. All surface soils were non-saline.

Particulate organic carbon

The relationship between total organic C and particulate (>53um) organic C is shown in Fig. 2. There is a high correlation across all sites, with particulate organic C comprising about 36% of total organic C on average. Note however that the mango sites are outliers (and not included in the regression); they have considerably higher particulate organic C per unit total organic C than other sites.

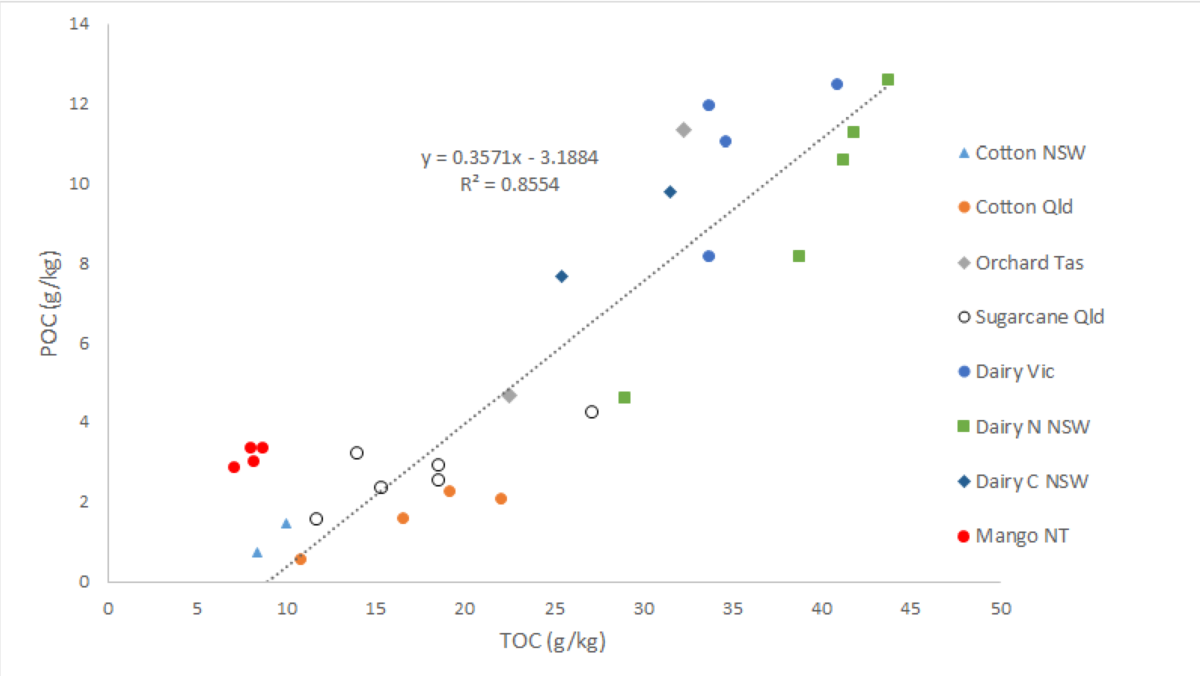


Figure 2. Relationship between total organic C and particulate organic C for MPfN surface soils. Mango sites from the Northern Territory have not been included in the correlation.

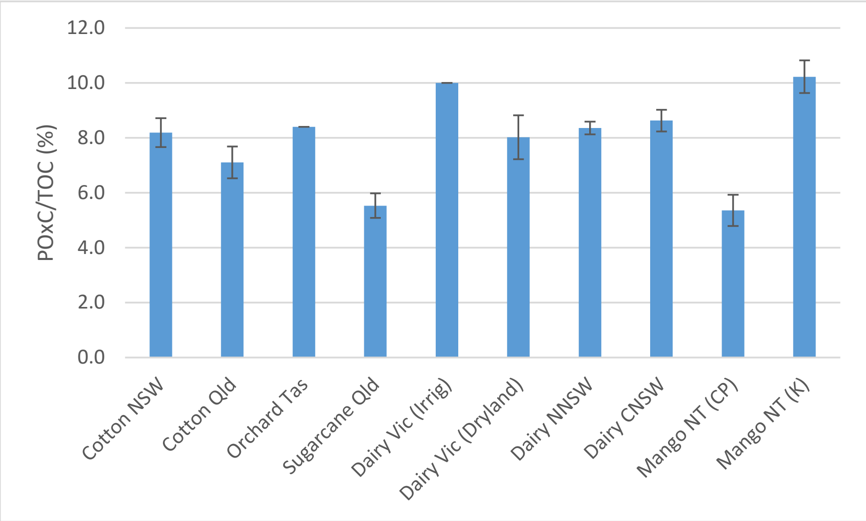
Labile carbon

Permanganate oxidisable C (POxC) is used in this study as an estimate of easily oxidisable, and therefore labile, soil organic C. The percentages of TOC and POC comprised of POxC are shown in Fig. 3a and Fig. 3b.

Table 1. Analyses for surface soil samples.

Cropping system	Sample ID						Whole soil fraction >53µm		POxC	PMN	
Location		Depth	pH_w	EC	TOC	TN	POC	PON	($KMnO_4$)	7 days	14 days
		(cm)		(dS/m)	(g/kg)	%	(g/kg)	(g/kg)	(g/kg)	(mg/kg soil)	
Cotton NSW	SR16087	(0-15)	8.3	0.11	8.4	0.09	0.8	0.1	0.7	0.7	-4.2
	SA170087		8.1	0.12	10.0	0.10	1.4	0.1	0.8	5.3	3.2
Cotton Qld	Naas Season 2016/2017	(0-15)	9.3	0.34	10.8	0.08	0.57	0.07	0.58	10.5	8.8
	Clapham Season 2016/17		8.5	0.11	16.6	0.13	1.6	0.1	1.3	7.3	8.4
	Naas Intensive 2017/18		8.6	0.22	22.1	0.20	2.1	0.1	1.7	13.7	19.9
	Naas Satellite 2017/18		8.7	0.15	19.2	0.16	2.3	0.2	1.5	20.6	9.9
Cherry Tas	Jericho, A4	(0-10)	6.2	0.25	32.3	0.26	11.3	0.7	2.7	24.5	33.0
	Wandin	(0-10)	5.7	0.10	22.5	0.20	4.66	0.34	1.81	19.0	27.6
Sugarcane Qld	Bundaberg	(0-20)	6.7	0.05	18.6	0.19	2.5	0.1	1.3	5.7	7.3
	Mackay		6.5	0.05	14.0	0.13	3.2	0.1	0.9	19.6	22.1
	Quabba		5.8	0.03	15.4	0.12	2.3	0.1	0.8	12.6	15.4
	Crisafulli		4.9	0.04	11.8	0.11	1.5	0.1	0.5	6.6	9.2
	Innisfail		5.2	0.04	27.2	0.17	4.2	0.2	1.5	21.3	27.1
	Tully		5.2	0.05	18.6	0.13	2.9	0.1	0.7	22.2	23.4
Dairy Victoria	Buffer zone/Irrigated	(0-10)	7.3	0.15	33.7	0.27	11.9	0.8	3.4	95.5	135.0
	Buffer zone/Dry land		7.1	0.14	40.9	0.31	12.5	0.8	3.0	113.1	115.0
	Control/Irrigated		7.1	0.16	34.6	0.27	11.0	0.7	3.4	79.7	95.6
	Control/Dry land		7.1	0.10	33.7	0.25	8.1	0.5	3.0	44.9	55.4
Dairy Northern NSW	Casino FT_10.5.16	(0-10)	5.7	0.47	43.8	0.43	12.57	1.00	3.46	96	126
	Casino ZT_10.5.16		5.9	0.32	41.9	0.40	11.24	0.85	3.72	83	119
	Casino ZT_8.3.2017		6.4	0.15	29.0	0.27	4.61	0.35	2.24	49.6	63.8
	Casino FT_28.3.2018		6.2	0.10	41.2	0.38	10.58	0.80	3.50	65.9	81.1
	Casino ZT_28.3.2018		6.4	0.10	38.8	0.36	8.14	0.55	3.40	70.2	82.7
Dairy Central NSW	Camden ZT	(0-10)	7.0	0.11	25.4	0.21	7.68	0.37	2.09	71.1	79.2
	Camden High N		6.7	0.13	31.6	0.28	9.78	0.58	2.84	90.7	104
Mango NT	Coastal Plains Control	(0-15)	5.6	0.03	7.1	0.06	2.87	0.40	0.34	7	10
	Coastal Plains Litter & Fertiliser		6.4	0.07	8.7	0.08	3.36	0.30	0.52	10	12.1
	Katherine Control		8.5	0.10	8.2	0.07	3.04	0.22	0.79	9	11.8
	Katherine Litter & Fertiliser		8.2	0.17	8.0	0.07	3.39	0.23	0.87	13	14.6

(a)



(b)

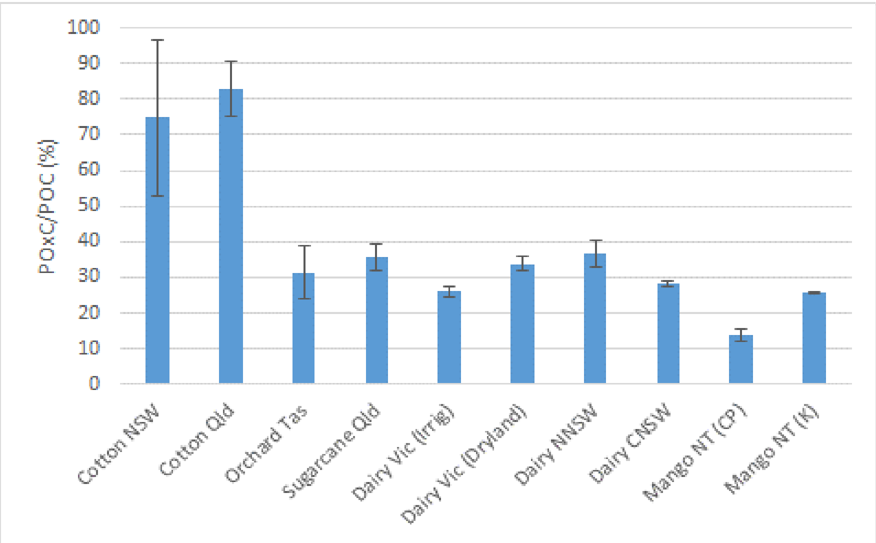


Figure 3. Plot of labile organic C (POxC) as a percentage of (a) total organic carbon (TOC) and (b) particulate organic carbon (POC) for different agricultural systems. Bars represent standard errors of the mean (SEM).

There was little difference in average POxC/TOC across most cropping systems, although labile C was a lower percentage of TOC for sugarcane and mango (Coastal Plains) sites (Fig. 3a). Note however, the standard errors of the mean (SEM) for dryland dairy sites in Victoria, and for the mango sites were large [coefficient of variation (CV) >10%], indicating between-site effects for these agricultural systems that might be related to differences in management practices at the sites.

For most systems, labile C (POxC) comprised between 25-35% of POC (Fig. 3b), with a lower percentage for mangoes at the Coastal Plains sites than the Katherine sites. Conversely, the cotton sites were very different to the other systems with POxC comprising more than 70% of the POC. The large SEMs (CV >10%) for NSW cotton, Qld cotton, orchard, sugarcane and dairy NNSW sites indicate between-site effects for these systems.

Organic carbon and organic N pools

The C/N ratios of organic matter in the bulk soil and C/N ratios of the particulate organic matter for the various cropping systems are presented in Table 2.

Table 2. Carbon-to-nitrogen ratios and standard errors of the mean (SEM) for bulk soil organic matter and particulate organic matter for the different agricultural systems. Highlighted cells have high SEMs (CV>10%).

System	Location	TOC/TON	POC/PON
Cotton	NSW	9.7±0.01	13.3±0.8
Cotton	Qld	12.3±0.5	13.5±0.4
Cherry	Tas	11.8±0.7	15.4±0.6
Sugarcane	Qld	12.6±0.9	27.5±4.3
Dairy	Vic	13.0±0.3	14.7±0.4
Dairy	NNSW	10.6±0.1	13.4±0.4
Dairy	CNSW	11.9±0.5	18.8±1.9
Mango	NT	12.1±0.3	16.4±0.6

There are few differences between agricultural systems in the C/N ratios for bulk soil and the particulate fraction (>53um), although the bulk soil C/N ratio of the NSW cotton sites is lower than other sites, and the C/N ratio of the particulate organic fraction for sugarcane sites is much higher than for other agricultural systems (Table 2). The high CVs of the particulate C/N ratios of sugarcane and central NSW dairy sites indicate considerable between-site variations.

Potentially Mineralisable Nitrogen

Mean and standard error values for PMN_{7d} and PMN_{14d} for the agricultural systems are presented in Table 3.

Table 3. Mean 7 day and 14 day Potentially Mineralisable N values and standard errors of the mean (SEM) for the MPfN agricultural systems.

System	Location	PMN 7d (mg/kg)	PMN 14d (mg/kg)
Cotton	NSW	3±2.3	-0.5±3.7
Cotton	Qld	13±2.8	11.8±2.7
Cherry	Tas	21.8±2.8	30.3±2.7
Sugarcane	Qld	15±3	17.4±3.3
Dairy	Vic	83±14.5	100.3±17.0
Dairy	NNSW	67±7.9	86.7±11.9
Dairy	CNSW	81±9.8	91.5±12.2
Mango	NT	10±1.1	12.1±1.0

Tropical-subtropical cropping systems (cotton, sugarcane, mango) have lower PMN_{7d} and PMN_{14d} than the orchard and dairy sites. Note that the NSW cotton sites demonstrated mean net 14 day immobilisation as a result of the large net immobilisation evident for site SR16087.

Potentially mineralisable N values for 7 day (PMN7d) and 14 day (PMN14d) incubations were highly correlated, with PMN14d being about 22% higher than PMN7d (Fig. 4).

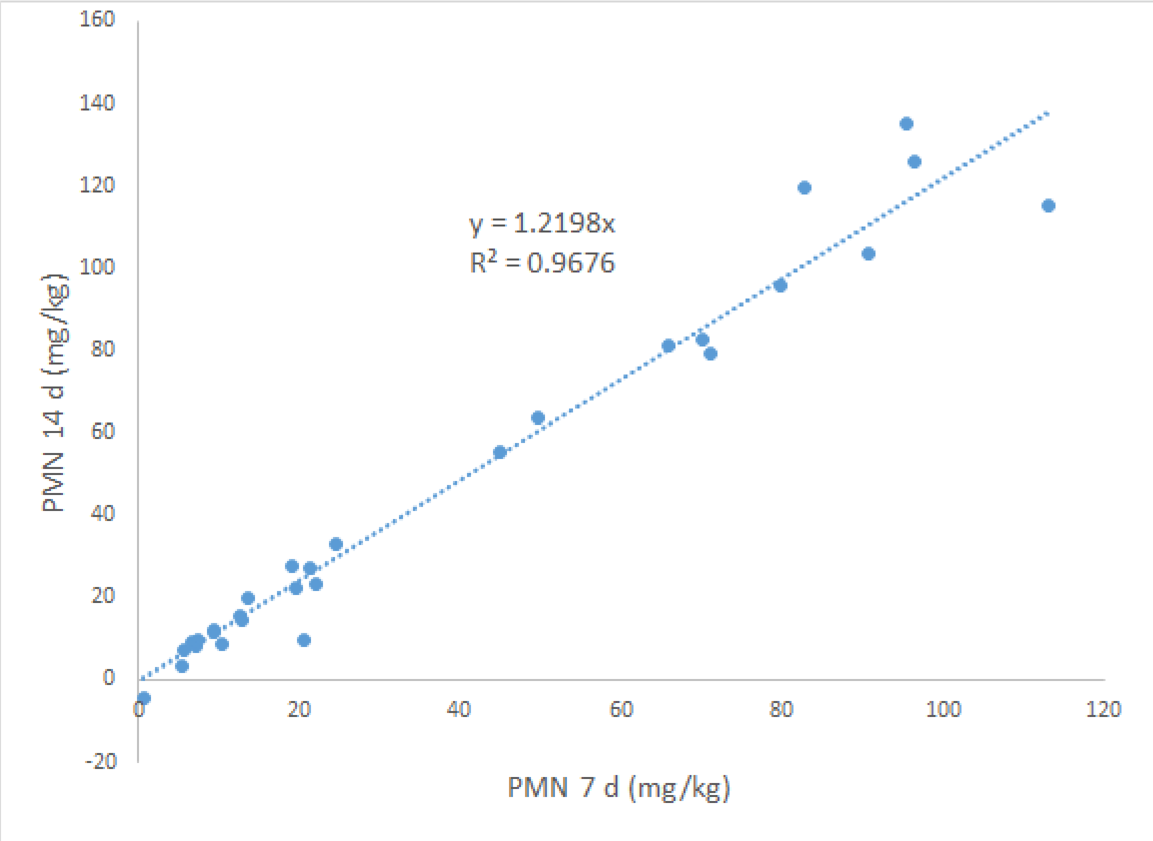


Figure 4. Relationship between potentially mineralisable N at 7 days and at 14 days for MPfN surface soils.

Soil properties correlated with Potentially Mineralisable Nitrogen

Step-up multiple linear regression was used to identify the soil organic C and N pools significantly impacting PMN_{7day}, PMN_{14day} and $PMN_{14day-7day}$. In this report, these PMN values are considered to be indicative of the following: PMN_{7day}- short term 'Birch effect' which is the flush of N mineralisation following re-wetting of air-dry soil; PMN_{14day}- longer term mineralisation inclusive of the Birch effect and steady state mineralisation rate obtained when soil is maintained at a constant soil moisture content; $PMN_{14day-7day}$- steady state mineralisation rate obtained when soil is maintained at a constant soil moisture content.

The soil properties tested in the regressions were: TOC, TN, POxC, POC and PON. The following variables best explained the variation in the PMNs, and in no case did the addition of other variables significantly (P=0.05) improve the regression.

$PMN_{7day} = f$ (POC) (R^2=0.817); $PMN_{14day}= f$ (POC) (R^2=0.839); $PMN_{14day-7day}= f$ (PON) (R^2=0.613)

Carbon dioxide evolution

Carbon dioxide evolution over 7 and 14 days showed no correlation with POxC (Fig. 5). The NSW cotton sites are highlighted for comparison with results in Fig. 6.

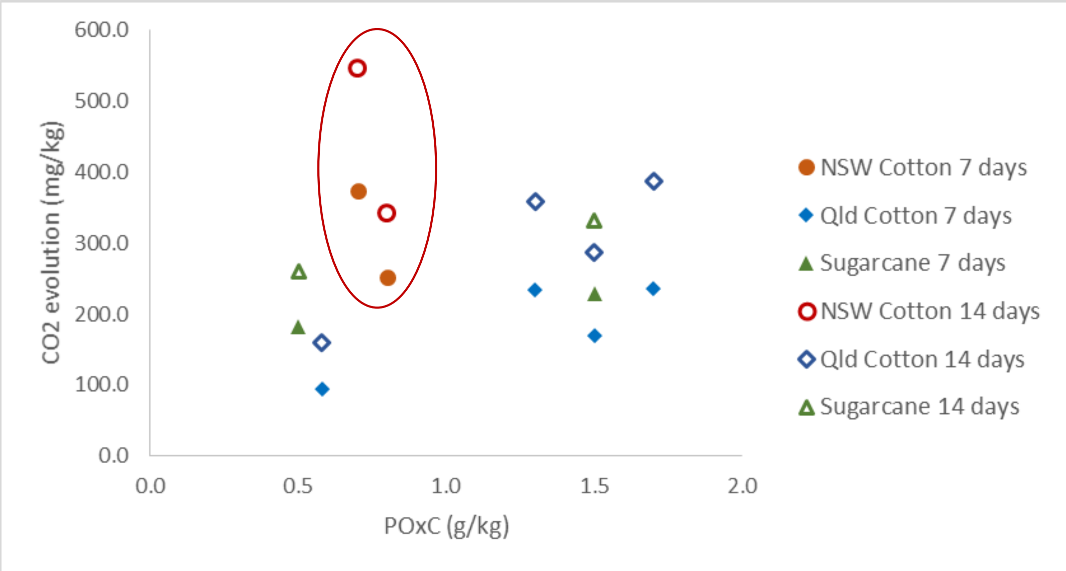


Figure 5. Carbon dioxide evolution over 7 and 14 days plotted against POxC for the MPfN surface soils.

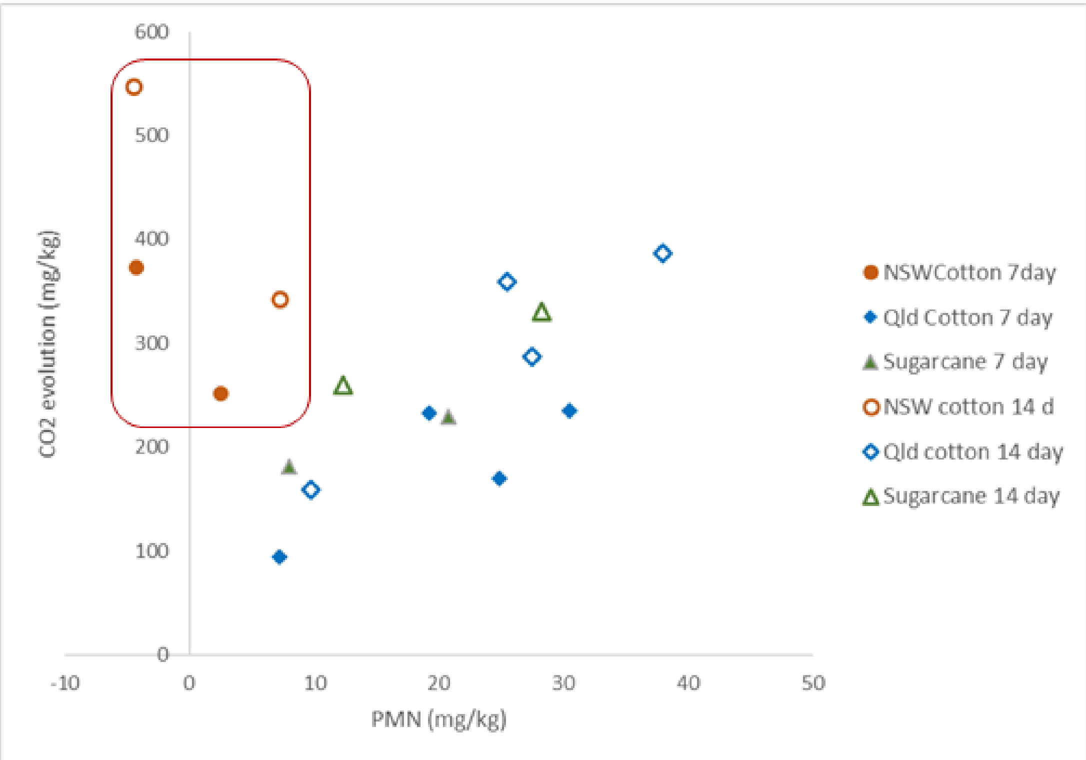


Figure 6. Carbon dioxide evolution over 7 and 14 days plotted against PMN for the MPfN surface soils.

When carbon dioxide evolution was plotted against PMN, there was a trend for PMN to increase with carbon dioxide evolution except for the NSW cotton soils.

Discussion

Organic C and N pools

The surface soils from the MPfN agricultural systems covered a wide range in soil pH (4.9-9.3) and TOC ranged from 7.1mg/kg to 43.8mg/kg (Table 1). For most agricultural systems, labile C (POxC) comprised from 8-10% of TOC (Fig. 3a), but the sugarcane cropping system had lower proportions of labile C, possibly as a consequence of the deeper sampling depth and dilution of the relative contribution of recent crop residues on the soil surface to the overall soil organic matter pool. Like the sugarcane sites, the Coastal Plains NT mango sites had a low proportion of labile C in the TOC, but contrary to the sugarcane and most other sites, the mango sites also had a low proportion of labile C in the particulate organic carbon fraction (Fig. 3b). In can be inferred from these results that the Coastal Plains NT mango soils are likely to be carbon-limited, yet this is not the case with the Katherine NT mango sites; the reason for this difference is not known.

The particulate organic C in the Qld and NNSW cotton sites was much higher in labile C than all other sites (Fig. 3b) highlighting the greater importance of particulate organic matter as a carbon source in the cotton cropping system compared to the other systems.

Across all systems, the average C/N ratio for the particulate organic matter was 13.9, compared with a C/N ratio of 11.7 for the soil organic matter (Table 2). This reflects the further biological processing that the particulate organic matter needs to go through before it is converted to stable soil organic matter.

Mineralisable N

The low lability of the TOC in sugarcane soils coupled with the high C/N ratio of the particulate fraction is the likely cause of the low mineralisable N results for these soils. The mango sites also had low mineralisable N, likely a consequence of the low lability of the TOC and POC fractions (Fig. 3a, b) and the comparatively high POC/PON ratio.

Over 7 and 14 days, all sites showed net N mineralisation except the NSW cotton soils; for the latter soils, the SR site samples demonstrated net immobilisation at 14 days, as did two of the six SA site samples. Initial soil ammonium-N concentrations were low and similar in all cotton soils (NSW cotton: 2.3$\pm$0.2; Qld cotton: 4.0$\pm$0.5), but the average Day 0 nitrate-N for the NSW cotton sites was 7.8$\pm$2.6 mg/kg compared to 25.9$\pm$5.9 mg/kg for the Qld cotton sites; the latter soils showed net N mineralisation, albeit low. Whether net N mineralisation or net immobilisation occurs in cotton soils therefore depends on the initial soil mineral N content.

The sugarcane soils had higher initial ammonium-N (12.1$\pm$1.6 mg/kg) than the cotton soils, and low nitrate-N (6.2$\pm$0.9 mg/kg. However, the low lability of the soil organic C and particulate organic C in the cane soils (Fig 3a, Fig 3b) would have restricted microbial activity, and resulted in net low rates of N mineralisation (Table 3).

Despite the wide range of crop residues, there was a high correlation between POC and TOC (Fig. 2) except for mangoes where POC was higher per unit TOC than any of the other cropping systems. Compost was added to some of the surface soils of the mango cropping system to improve soil health and this would explain these results.

Potentially mineralisable N at 14 days was only 22% higher than PMN7d (Fig. 4) illustrating the disparity between the Birch effect mineralisation rate and the steady state mineralisation rate. A similar observation was made by Allen et al. (2018) for sugarcane soils; they found a two-rate model best fitted N mineralisation over 300 days at 35°C, with the initial high rate (Birch effect) decreasing very much after 10-20 days.

As reported earlier in the report, POC was the primary driver of 7 and 14 day soil N mineralisation across all agricultural systems. However, using CO_2 evolution as an index of soil microbial activity and oxidation of organic matter, it is evident that microbial activity is not impacted by the level of labile POC in cotton and sugarcane soils (Fig. 5), and Figure 6 shows that PMN tends to increase as CO_2 evolution increases in Qld cotton and sugarcane soils, but not in NSW cotton soils. As mentioned earlier, the net immobilisation observed in the NSW cotton soils is caused by their low initial mineral N content relative to that of the Qld cotton soils (10.1 mg N/kg soil and 29.9 mg N/kg soil, respectively).

Allen et al. (2018) did not measure POC or PON in their study, but found TN better correlated with PMN_{14day} than any measure of organic C. The greater importance of organic N than organic C in their study is probably a consequence of the comparatively small range of organic C in their soils (all sugarcane) compared to the wide range observed in the MPfN soils (which included dairy pastures). However, the high correlations between TOC and TN (R^2=0.95) and POC and PON (R^2=0.95) in the MPfN soils indicate that a measure of either organic C or organic N could be used to infer potential N mineralisation.

Acknowledgements

I am grateful to the MPfN Project Leaders and teams who provided their soil samples for these additional analyses which I hope will be useful to them.

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