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Research paper

Impact of agricultural management practices on the nutrient supply potential of soil organic matter under long-term farming systems

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ABSTRACT

Soil organic matter (SOM) has the potential to supply substantial quantities of nutrients [*i.e* nitrogen (N), phosphorus (P) and sulphur (S)] for plant uptake. Yet there is little understanding of the impact of management on the nutrient supply potential in soils (particularly, P and S). To quantify N, P and S availability from SOM, surface soils (0–10 cm) were collected from 14 management practices across three long-term (16–46 years) experimental sites under semi-arid (Luvisol), Mediterranean (Luvisol) and sub-tropical (Vertisol) environments in Australia. The practices comprised conventional (CT) and reduced tillage (RT) with mixed farming, no-till with continuous cropping (NT), and perennial pasture (PP) in the semi-arid Luvisol, while in a Mediterranean direct-drilled continuous cropping system, stubble was either retained (SR) or burnt (SB). Practices on the Vertisol comprised a factorial combination of CT, NT, SR, SB with either 0 (0N) or 90 kg urea-N ha^{-1} (90N) in a continuous cropping system. Soils were incubated under controlled soil moisture and temperature, and cumulative organic C mineralised (C_{min}), and net available N, P and S were measured over 126 days. In the semi-arid Luvisol, CT and/or RT showed significantly higher C_{min} and net available N, P and S than NT and PP. In the Mediterranean Luvisol, C_{min} and net available P were not influenced by stubble management. In the Vertisol, CT-SR (*cf.* CT-SB and NT-SR/SB) with or without N fertilisation significantly increased C_{min}, and CT-SR and/or -SB with N fertilisation (*cf.* CT-SR/SB without N fertilisation and NT-SR and/or -SB with or without N fertilisation) significantly increased net available N and P. This study found a continuous release of net available N (11–49 kg N ha^{-1} over 126 days) across all management practices, whereas, the release of available P and S was evident only during the first 30 days (6–74 kg P ha^{-1}, −4 to 22 kg S ha^{-1}), after which microbial immobilisation or clay fixation of P and S predominated, particularly in the Vertisol. In conclusion, the results indicate that SOM is a ready source of plant available P and S (in addition to N), and tillage and stubble retention generally enhanced SOM mineralisation and nutrient release, which varied with soil type.

1. Introduction

Soil organic matter (SOM) is a key indicator of soil quality and plays an important role in enhancing a range of soil physical, chemical and biological functions (Murphy, 2015). SOM is both a source and sink of organic forms of carbon (C) and major plant nutrients, such as nitrogen (N), phosphorus (P), and sulphur (S) (Kirkby et al., 2011; Murphy, 2015). Over the last decade, there has been increasing interest on the impact of agricultural management practices on SOC and nutrient cycling and storage worldwide, including in Australia (Bhupinderpal-Singh et al., 2004, 2006; Dalal et al., 2011; Hoyle and Murphy, 2011; Hoyle et al., 2013; Kopittke et al., 2016a,b). However, knowledge of how management practices influence availability of nutrients for plant growth, a key function of SOM, across diverse managed agro-ecosystems is limited (Hoyle and Murphy, 2011; Murphy 2015).

The nutrient contents of soil may be maintained or enhanced by

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certain management practices, possibly facilitated by high organic matter inputs or retention into the system. For example, long-term no-till (NT) with stubble retention (SR) along with fertilisation in cropping systems, and mixed crop–pasture and perennial pasture (PP) dominated farming systems are usually recommended as improved management systems which may increase or maintain SOM and associated nutrients (Bhupinderpal-Singh et al., 2004; Dalal et al., 2011; Hoyle et al., 2013; Kopittke et al., 2016b). These and other contrasting practices such as conventional tillage (CT), reduced tillage (RT) and stubble burning (SB) may impact soil microbial biomass and activity differently (Haynes 1999; Hoyle and Murphy, 2011; Rui et al., 2016) and the physical-chemical environment (Luo et al., 2010; Page et al., 2013), and consequently the release plant available nutrients from SOM reserves (Guppy et al., 2005; Hoyle and Murphy, 2011; Curtin et al., 2016; Rui et al., 2016).

Studies have shown that CT breaks down soil structure (Six et al., 2000), increases soil aeration (Carter et al., 1994), and exposes mineral protected SOM to microbial attack (Gathala et al., 2011; Zhang et al., 2013). As a result, there is the potential to release high quantities of plant available nutrients through SOM mineralisation (Hoyle and Murphy, 2011; Dimassi et al., 2014). On the other hand, in a 100-day incubation study, Curtin et al. (2014) found that the cumulative SOC mineralisation per unit mass of SOC in an undisturbed perennial pasture system was almost double that of arable cropping systems, likely due to relatively high plant C input and relatively labile SOC in perennial pasture systems (Crawford et al., 2000). However, other studies reported that improved land management (*e.g.* PP or NT) may preserve soil structure (Six et al., 2000; Devine et al., 2014), while protecting SOC in micro-/macro-aggregates (Six et al., 2000), reducing soil pore spaces (Jensen et al., 1996), and consequently decreasing soil microbial biomass and activity (Raiesi, 2006; Tan et al., 2015). Thus, it is important to understand the impact of alternative agricultural management practices on the nutrient supply potential of SOM, and this knowledge can thus be useful to optimise productivity and profitability of farming systems.

The rate of turnover for SOM *via* mineralisation and the associated nutrient supply with different management practices also varies depending on soil texture and clay minerology. Soils with a high proportion of clay-sized particles provide greater stabilisation of SOM than soils dominated by sand-sized particles (Christensen, 2001). Furthermore, clay-rich soils dominated by 2:1 clay minerals (such as smectite *versus* kaolinite) provide larger specific surface areas and numerous reactive sites where SOM and nutrients can be adsorbed *via* ligand exchange and polyvalent cation bridging to lower SOM mineralisation (von Lützow et al., 2007; Saidy et al., 2013; Lehmann and Kleber, 2015). Also, the self-mulching nature of smectitic-rich soils, for example, Vertisols, may override the effect of tillage on SOC mineralisation (Dalal et al., 2011).

In Australia, few long-term farming system trials exist and although a number of studies have examined the influence of management practices on SOC accumulation and mineralisation rates, and soil microbial activity (Hoyle and Murphy, 2006; Thomas et al., 2007; Dalal et al., 2011), far fewer have considered the subsequent nutrient value of SOM for plants (Raiesi, 2006). The aims of this study were therefore to quantify the impact of long-term management practices on the dynamics of SOC mineralisation and net supply of plant available N, P and S in different soils (Luvisol *versus* Vertisol) under contrasting tillage, cropping and/or pasture systems. Consistent with common paradigms, we expected higher SOC mineralisation and net release of plant available nutrients in systems with high *versus* no tillage intensity, and/or where stubble was retained *versus* burnt or where N fertiliser was applied, regardless of soil type. Further, soils such as Vertisol, which is rich in smectite and possibly also polyvalent cations, could significantly impact the release of plant available nutrients, particularly P and S, once organic matter depletes during decomposition, compared with relatively clay-poor Luvisol.

Table 1
Basic information of the long-term sites, including soil properties (0–10 cm depth). Values in brackets are standard errors (n = 3).

	Condobolin	Merredin	Hermitage
Soil classification	Luvisol	Luvisol	Vertisol
Coordinates	33°05′19″S, 147°08′58″E	31°28′S, 118°16′E	28°12′S, 152°06′E
Trial established	1998	1987	1968
Mean annual rainfall (mm)	~461[a]	~325[a]	~682[b]
Rainfall distribution	No clear seasonality	Winter-dominant	Summer-dominant
Mean annual min (°C)	~10[a]	~11[a]	~10[b]
Mean annual max (°C)	~25[a]	~25[a]	~24[b]
WHC (g g^{-1})	0.30(0.4)	0.26(0.3)	0.56(0.3)
Sand/%	62(2.0)	66(0.8)	15(2.6)
Silt/%	11(1.3)	8(1.2)	22(2.5)
Clay/%	27(0.8)	25(0.7)	63(1.2)
Bulk density (g cm^{-3})	1.3 − 1.5	1.3	1.1
Na^+ (cmol kg^{-1})	0.13(0.01)	0.62(0.1)	1.3(0.2)
K^+ (cmol kg^{-1})	2.1(0.1)	0.97(0.04)	1.1(0.1)
Ca^{2+} (cmol kg^{-1})	6.2(0.1)	3.5(0.4)	28(0.4)
Mg^{2+} (cmol kg^{-1})	1.9(0.05)	3.3(0.4)	25(0.7)
Fe_d (mg kg^{-1})	18150(450)	4280(90)	12650(150)
Al_d (mg kg^{-1})	1060(20)	568(22)	2040(20)
Clay minerals	Mi–Kaol–Sm***, Qtz**,Hem**, Goe**, Ant*	Kaol***, Mi **, Qtz*, Ant*, Ort*	Sm***, Kaol**

Mi = mica; Kaol = kaolinite; Sm = smectite; Qtz = quartz; Goe = goethite; Hem = hematite; Ant = anatase; Ort = Orthoclase. The asterisks ***, **, * represent > 60% (dominant or co-dominant), 5–20% and < 5%, respectively.

[a] 1987–2016.

[b] 1996–2016.

2. Materials and methods

2.1. Site descriptions

Long term field trial sites were selected for this study as SOC concentrations take many years to reach a new equilibrium when land use or management practices are changed (Lam et al., 2013). The sites include: (i) a 16-year-old (established in 1998) farming system trial at the Condobolin Agricultural Research and Advisory Station, New South Wales; (ii) a 27-year-old (established in 1987) crop stubble management trial at the Merredin Research Station, Western Australia; and (iii) a 46-year-old (established in 1968) tillage-stubble-N fertiliser management trial at the Hermitage Research Station, Queensland. The site information and basic soil properties (0–10 cm depth) are given in Table 1. For analysing most of the basic soil properties, such as soil texture, clay mineralogy, water holding capacity (WHC), and basic cations (Table 1), soil samples were composited across the practices because of their limited impact on these properties.

At the Condobolin site, the following four treatments were selected: (1) CT and (2) RT under mixed pasture–wheat farming systems; (3) NT under continuous cropping system; and (4) PP. The experimental plots across the four major farming systems were established in 1998 in a randomised block design, with five rotational phases and four replicates (Central West Farming System Inc., 2015). The rotations in the CT treatment were: long fallow-wheat (LFW; *Triticum aestivum* L.), short fallow-wheat (SFW) with under-sown pasture, and three years of grazed pasture. The rotations in the RT treatment were: LFW, no crop, LFW with under-sown pasture, and two years of grazed pasture. The rotations in the NT treatment were: wheat, barley, pulse, wheat, pulse/green manure. Stubbles were incorporated in the CT treatment, while in the RT and NT treatments stubbles were retained on the soil surface. Tillage was performed to 10 cm depth using a chisel tyne with two to three passes in the CT, and to 2 cm using a trash-worker with one pass in the RT (Fang et al., 2016). The rotational phases in the cropping systems at the time of soil sampling were: (a) after wheat (*Triticum aestivum* L.) phase that was transitioning to pasture in the CT and RT

treatments; and (b) after barley (*Hordeum vulgare* L.) phase that was transitioning to the next pulse crop in the NT treatment.

The Merredin site consisted of a predominantly legume–wheat based continuous cropping system, where stubble was either burnt just prior to drill sowing (autumn burn, SB) or retained as standing stubble (SR) after harvest. The trial was seeded in 16-row plots (5 m in width and 30 m in length) in a randomised block design with six replicates. Basal fertiliser was applied during seeding using 80-mm-wide press wheels with following chains. The rotational phase prior to sampling was wheat (*Triticum aestivum* L.).

At the Hermitage site, eight treatments were selected in the continuous cropping system trial (Dalal et al., 2011), involving a factorial combination of tillage (CT and NT), stubble management (SR and SB), and N fertilisation (0N and 90N, fertiliser N applied at 0 and 90 kg N ha^{-1} yr^{-1} as urea, respectively) arranged in a randomised block design with four replicates. In the CT treatment, tillage was performed to 10 cm depth with four to five passes of a chisel plough during the fallow period each year (December to June). After crop harvesting, stubble was incorporated into the CT treatments during ploughing, while in the NT treatment stubble was retained on the soil surface. In the stubble burnt treatment, the stubble was burnt in the field immediately after the crop harvest, and before the first tillage operation. Each of the fertilised treatment received 90 kg N ha^{-1} every year in June at the sowing of wheat (*Triticum aestivum* L., cv. Baxter) or barley (*Hordeum vulgare* L., cv. Clipper) (For further details, see Dalal et al., 2011).

2.2. Soil sampling and processing

A composite soil sample of 12–15 cores was collected using a coring rig (with the core diameter 7.6 cm) in early May 2014 at 0–10 cm depth in a random zigzag pattern from three selected replicated plots at each field site. In total we collected 42 composite samples (12 samples at Condobolin, 6 samples at Merredin and 24 samples at Hermitage). Soil samples were collected prior to crop sowing (*i.e.* autumn fallow) from all three field sites or at the same time in the perennial pasture system (at Condobolin).

Immediately after sampling, field-moist soils were stored at 4 °C until further processing. Soils were sieved sequentially through a 12-mm and then a 6.5-mm sieve by gently breaking the soil cores along planes of weakness by hand while preserving soil aggregation. Visible plant debris (> 2 mm) and gravel were removed with tweezers. The soil samples were then air-dried in a controlled temperature room (~22 °C) for approximately two days to lower the moisture content to ~20–25% of WHC and the air-dried samples were stored at 4 °C.

2.3. Soil physical and chemical analysis

Basic soil properties [soil pH, WHC, soil texture, total soil C, N, P and S content and particulate organic carbon (POC)] were measured using the air dried sieved (< 2 mm) soil samples. Soil pH was measured in 1:5 soil:water suspension using a glass electrode (Rayment and Higginson, 1992). The soil WHC (moisture content at field capacity) was determined according to the procedure of Jenkinson and Powlson, (1976) after draining the water-saturated soil for 40 h. The percentages of sand, silt and clay in soil samples were determined by the hydrometer method after dispersing soil with 10% sodium hexametaphosphate (Gee and Bauder, 1986). Soil exchangeable cations (Na, K, Ca and Mg) were analysed by atomic absorption spectroscopy (AAS) after extraction with ammonium acetate. The contents of sodium citrate dithionite-extractable iron (Fe_d) and aluminium (Al_d) in soil were determined according to the procedure of Blakemore et al. (1987). A 10 g subsample of the air dried sieved (< 2 mm) soil was further dried at 60 °C for 24 h and ground to fine powder (< 0.053–0.080 mm) using a MM400 Mixer Mill grinder (Retsch GmbH, Haan, Germany). The ground soil samples were analysed for total C, N, and S by an Elementar vario EL cube CHNS analyser (Table 2). Total P in soil was analysed using a PANalytical Epsilon 3 X-ray fluorescence spectrometer (Rayment and Lyons, 2011). Particulate organic C (POC) content in the soils was also determined (Devine et al., 2014). Briefly, a 5 g subsample of the air dried sieved (< 6.5 mm) soil was dispersed using 0.5% Na-hexametaphosphate (1:5 ratio) and total C in the finely ground soil fraction was analysed by an Elementar vario EL cube CHNS analyser (see Supporting information; Table S3).

Table 2
Soil pH and stocks of total soil organic carbon (SOC) and nutrients [nitrogen, N; phosphorus, P; and sulphur, S] in Luvisol and Vertisol (0–10 cm). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

Treatments	Soil pH	Total SOC	Total N	Total P	Total S
		t ha^{-1}			
		Condobolin (Luvisol)			
CT	6.2	17.6	1.48	0.57	0.28
RT	6.3	18.6	1.57	0.61	0.26
NT	5.9	18.9	1.67	0.71	0.26
PP	6.2	20.4	1.74	0.59	0.30
$LSD_{0.05}$	0.2	2.6	0.25	0.10	0.03
		Merredin (Luvisol)			
SR	6.4	11.6	0.93	0.42	0.30
SB	6.6	11.4	0.81	0.44	0.28
$LSD_{0.05}$	0.8	1.9	0.21	0.07	0.05
		Hermitage (Vertisol)			
CT-SB-0N	8.0	21.1	1.20	1.16	0.17
CT-SB-90N	7.6	22.7	1.26	1.17	0.20
CT-SR-0N	7.9	21.1	1.18	1.10	0.19
CT-SR-90N	7.4	22.4	1.35	1.17	0.23
NT-SB-0N	7.1	20.4	1.21	1.18	0.14
NT-SB-90N	7.1	21.7	1.45	1.14	0.19
NT-SR-0N	7.1	20.9	1.33	1.18	0.16
NT-SR-90N	7.1	23.2	1.43	1.22	0.22
$LSD_{0.05}$	0.6	1.6	0.16	0.09	0.05

CT = conventional tillage; RT = reduced tillage; NT = no-till; PP = perennial pasture; SR = stubble retention; SB = stubble burnt; 0N = 0 kg urea-N ha^{-1}; 90N = 90 kg urea-N ha^{-1}.

Soil samples were fractionated into five aggregate-size classes using dry and wet sieving methods proposed by Devine et al. (2014) and Six et al. (1998). See Supporting information for detailed aggregate fractionation procedures and the calculation for mean weight diameter (MWD) of dry and wet aggregates, and aggregate stability index.

2.4. Laboratory incubation

The incubation experiment was conducted in closed and sealed 1200 ml buckets containing a CO_2-trap (30 ml, 2 M NaOH in a 70 ml container) and a container with deionised water (20 ml water in a 30 ml container) to maintain a constant humidity. The samples were incubated in a controlled temperature room at 22 ± 0.5 °C for 126 days. The experiment comprised 14 treatments from three field sites and three selected field replicates. Within each bucket, the air-dried sieved soil (see Section 2.2), equivalent to 33 g oven dried soil (~35 g of whole soil) from the 0–10 cm depth, was weighed into three 70 ml plastic containers (adjusted to 1.1 g cm^{-3}), which were periodically collected and sub-sampled at 10, 30 and 126 days for various analyses (see below). Appropriate volume of deionized water was added to each soil container to adjust the soil water content to 60% of field WHC at the start of incubation, ranging from ~0.16–0.18 g g^{-1} (Luvisols) to ~0.33 g g^{-1} (Vertisol); these soil water contents were periodically maintained during incubation. Although the water filled pore spaces varied across the treatments and soil types, ranging from ~0.30–0.34 m^3 m^{-3} (Luvisols) and ~0.62 m^3 m^{-3} (Vertisol), the targeted 60% of field WHC was intended to achieve optimal SOC and nutrient mineralisation, microbial biomass and metabolic quotient for each of these two soils (Franzluebbers, 1999).

2.5. Measurement of soil organic carbon mineralisation

The CO_2-C derived from SOM mineralisation was measured to indicate changes in biological activity using NaOH traps (Singh and Cowie, 2014) removed at 3, 10, 30, 60, 90 and 126 days after the start of the incubation. After removing soil containers on day 10 (for microbial biomass analysis) or on day 30 (for N, P and S extractions - see below), the volume and concentration of NaOH was decreased from 30 ml of 2 M solution, to 20 ml 1 M solution to account for the lower volume of incubated soils. Background CO_2-C was also measured using buckets containing only NaOH (without any soil) in triplicate. The CO_2-C evolved during incubation was measured by titration of the excess NaOH with 0.1 M HCl using phenolphthalein as an indicator, after the dissolved carbonates were precipitated with excess $BaCl_2$ (Singh and Cowie, 2014).

The cumulative proportion of the SOC mineralised over the 126 days incubation across all treatments was fitted to a two-pool exponential decay model to estimate mean residence time (MRT) of model-derived labile and recalcitrant SOC pools (Fang et al., 2014; see Supporting information).

2.6. Soil microbial biomass C and N

Soil microbial biomass C (MBC) and microbial biomass N (MBN) were determined using a chloroform fumigation–extraction procedure (Brooks et al., 1985; Vance et al., 1987). Briefly, the fumigated soil (~20 g) and an equivalent amount of non-fumigated soil (on the day of fumigation) were extracted with 80 ml of 0.5 M K_2SO_4 for 1 h. Total C and N in the fumigated and non-fumigated extracts were analysed using a Shimadzu Analyser (TOC-L CPH/CPN, Japan). The released C and N from microbial biomass due to chloroform fumigation were calculated as the difference in extractable C and N, respectively, between the fumigated and non-fumigated soils, and conversion factors of 0.45 for MBC (Wu et al., 1990) and 0.54 for MBN were applied (Brookes et al., 1985).

As measures of microbial C use efficiency (Rui et al., 2016), soil microbial metabolic quotient (μg CO_2-C mg^{-1} MBC hr^{-1}) and microbial quotient (mg MBC mg^{-1} SOC) were calculated for each replicate at days 10 and 126.

2.7. Plant available N, P and S in soil

Concurrent with the measurement of SOC mineralisation, extractable N, P and S were also measured to provide estimates of potentially mineralisable nutrients. Extractable N, P and S were measured on day 0, 30 and 126 by extracting samples with 2 M KCl (Blakemore et al., 1987), 0.5 M $NaHCO_3$ (Colwell, 1963) and 0.016 M KH_2PO_4 (Tabatabai, 1982). Total extractable N was calculated as the sum of NH_4^+-N and NO_3^--N concentrations. Net nutrient available N, P and S following the simultaneous mineralisation (organic to inorganic forms), immobilisation (inorganic to organic forms) and fixation (adsorption on soil minerals and/or precipitation with metal cations) processes during SOM mineralisation over day 0–30 and day 0–126 were quantified using the following Eqs. (1)–(3):

$$\Delta N_{available} = Mineral\ N_{d30\ or\ d126} - Mineral\ N_{d0}, \quad (1)$$

$$\Delta P_{available} = Colwell\ P_{d30\ or\ d126} - Colwell\ P_{d0}, \quad (2)$$

$$\Delta S_{available} = Mineral\ S_{d30\ or\ d126} - Mineral\ S_{d0} \quad (3)$$

where, $\Delta N_{available}$, $\Delta P_{available}$ and $\Delta S_{available}$ represent the net change in available N, P and S, respectively, after either day 30 (d30) or day 126 (d126) of incubation from day 0 (d0). The net available N, P and S (mg kg^{-1} soil) at days 30 and 126 were then adjusted for field-based bulk density to obtain the net nutrient availability values in kg ha^{-1}. Soil bulk density at Condobolin was measured using a soil coring approach and the values under the CT, RT, NT and PP treatments were 1.31, 1.32, 1.51 and 1.42 t m^{-3}, respectively. Soil bulk density used for the Merredin site was 1.33 t m^{-3} for both SR and SB treatments, which was measured using the NDM (gamma–neutron density meter) method (Holmes et al., 2011). The average soil bulk density across all the treatments at Hermitage was 1.10 t m^{-3} (Dalal et al., 2011).

2.8. Statistical analysis

Repeated measure analysis was performed for cumulative SOC mineralisation and SOC mineralisation rates over the study period for each site using a linear mixed model. Each analysis consisted of fixed effects of management, time and all interactions, and random effects of replicate, and either allowing for autocorrelated order 1 (AR1) or antedependence order 1 correlated residual errors within plots. For net available N, P and S (kg ha^{-1}) released from SOM *via* mineralisation at 30 and 126 days, as well as soil microbial biomass C and N, metabolic quotient and microbial quotient at 10 and 126 days after incubation, a linear mixed model was fitted with fixed effects of management and their interactions (Hermitage site), and random effects of replicate at each site. All models were fitted in the ASReml statistical package (Butler et al., 2009) within the R statistical software environment (R Team, 2014). The Wald-type F statistics were calculated for all fixed effects (management and for repeated measures, time) and all associated interactions. Predicted means for management were compared using the least significance difference at 5% level for each analysis (univariate) or at each time point (repeated measures).

3. Results

3.1. Soil carbon and nutrient stocks and soil pH

At Condobolin and Merredin, the management practices had no effect on SOC and total nutrient (N, P and S) stocks in the Luvisols at 0–10 cm depth (Table 2). At Condobolin, the NT *versus* CT, RT and PP treatments had lower soil pH, while at Merredin, soil pH was similar across the SR and SB treatments (Table 2). At Hermitage, the NT-SR-90N treatment had higher ($P < 0.1$) SOC and total N and S stocks, and the CT-SR-0N had higher ($P < 0.01$) soil pH, than the other treatments (Table 2).

3.2. Total soil organic carbon mineralisation

At the Condobolin site, management practices had a significant effect ($P < 0.001$) on the cumulative amount of SOC mineralised (C_{min}) over the study period (Table S1). At this site, 88–162 mg and 185–253 mg CO_2-C kg^{-1} soil were released after 30 and 126 days, respectively, across different management practices (Fig. 1a). The C_{min} under CT was significantly higher ($P < 0.001$) than RT, PP and NT over the study period (Table S1). Total SOC mineralisation rate was higher up to 30 days in the CT, RT and/or PP treatments compared to the NT treatment, and decreased in an exponential manner with time across all the treatments (Fig. S1). At the Merredin site, there was no significant effect of the stubble management practices on C_{min}, releasing 136–187 mg CO_2-C kg^{-1} soil over 30 days, and 472–555 mg CO_2-C kg^{-1} soil over 126 days, across the SR and SB treatments (Fig. 1b). Total SOC mineralisation rate at Merredin was initially higher ($P < 0.1$) in the SR than SB treatment (14 *cf.* 9 mg CO_2-C kg^{-1} soil d^{-1}), which decreased rapidly up to day 10, and then stabilised (3–5 mg CO_2-C kg^{-1} soil d^{-1}) over time across both SR and SB treatments (Fig. S1). At the Hermitage site, the interaction between tillage and stubble management had a significant effect ($P < 0.001$) on C_{min}, but the interaction between tillage and stubble with N fertiliser had no significant effect on C_{min} at days 30 and 126 (Fig. 1c, Table S2). Results showed that, after 126 days, 244–410 mg CO_2-C kg^{-1} soil was released across different management practices and the CT-SR with or without N

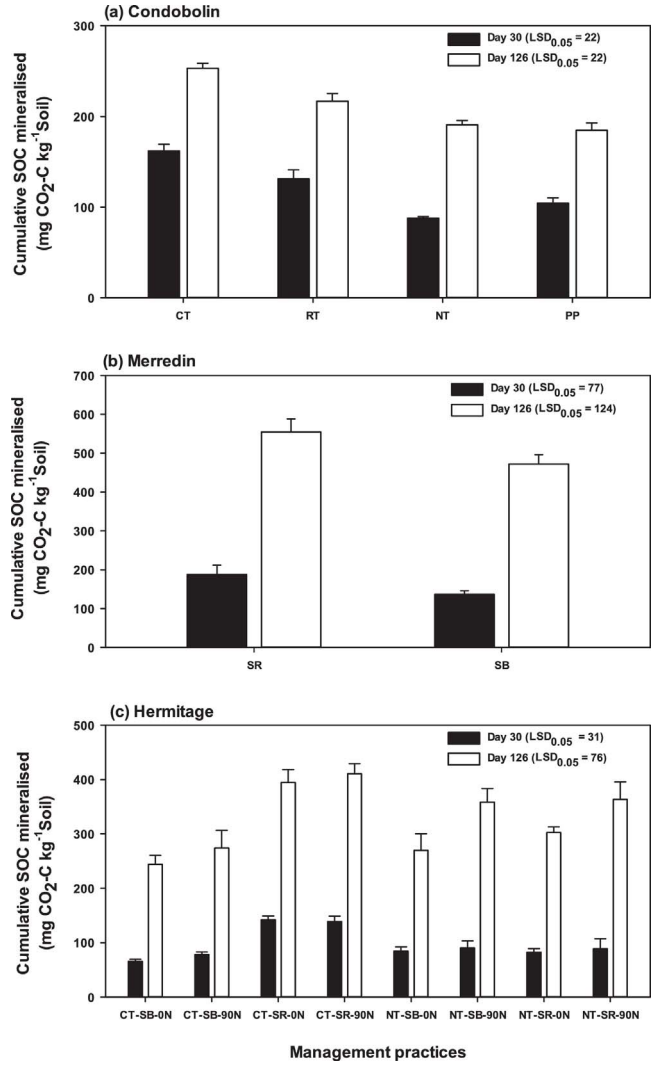

Fig. 1. Impact of contrasting management practices on the cumulative soil organic carbon (SOC) mineralised (mg CO_2-C kg^{-1} soil) at 30 days (dark bars) and 126 days (white bars) from incubated soils collected (0–10 cm depth) from long-term experimental sites at (a) Condobolin (New South Wales), (b) Merredin (Western Australia), and (c) Hermitage (Queensland). Legends: conventional tillage (CT), reduced tillage (RT), no-till (NT) and perennial pasture (PP) treatments at the Condobolin site; stubble retained (SR) and stubble burnt (SB) treatments at the Merredin site; and factorial combinations of CT, NT, SR, SB, no urea-N (0N) and 90 kg urea-N ha^{-1} yr^{-1} (90N) at the Hermitage site. See further details of the treatments in Methods. Error bars represent ± standard error of the means (n = 3). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

fertilisation resulted in the greatest C_{min} relative to the other treatments (CT-SB or NT-SR and NT-SB with or without N fertilisation). Total SOC mineralisation rate at Hermitage was initially higher in the CT-SR with or without N fertilisation treatments (18–22 mg CO_2-C kg^{-1} soil d^{-1}) compared to other treatments (6–9 mg CO_2-C kg^{-1} soil d^{-1}), which decreased rapidly at day 10 and then stabilised (1–4 mg CO_2-C kg^{-1} soil d^{-1}) over time across all the treatments (Fig. S1). When expressed as per unit of SOC (g) present in the soil, depending on management practices, 1.3–1.9% of total SOC was mineralised in the Luvisol at Condobolin, 5.5–6.2% in the Luvisol at Merredin, and 1.2–2.0% in the Vertisol at Hermitage, after 126 days of incubation (Fig. 2).

3.3. Mean residence time of soil organic carbon

The estimated MRT of recalcitrant SOC at Condobolin ranged between 55 and 87 years and varied significantly ($P < 0.001$) between the management practices: NT and PP had the longest MRT of recalcitrant SOC compared to CT and RT (Tables 3 and S1). At the Merredin site, the MRTs were similar in the SR (6.1 years) and SB (6.6 years) treatments. At the Hermitage site, CT and/or NT with SB with and without N fertilisation showed significantly ($P < 0.001$) longer (22–30 years) MRT compared to CT and/or NT with SR with and without N fertilisation (20–24 years). At the Condobolin site, the labile C constituted 0.7–1.6% of total SOC, with MRT of 14–30 days: while at the Merredin site, the labile C constituted 0.2–0.6% of total SOC, with MRT of 2–6 days (Table 3). At the Hermitage site, the labile C constituted 0.1–0.3% of the total SOC, with MRT only 1–3 days (Table 3).

3.4. Management impact on soil microbial properties

Soil microbial properties, that is, microbial biomass C (MBC), microbial biomass N (MBN) and microbial quotient, varied significantly ($P < 0.05$) with management practice at Condobolin (Table S1): the NT had lower MBC, MBN and microbial quotient than the CT, RT and PP treatments over the study period (Table 4). However, at the Merredin site, stubble management had no effect on these soil microbial properties. At the Hermitage site, soil MBC, MBN and microbial quotient were significantly ($P < 0.01$) affected by the tillage practices only over the study period, while both tillage and fertilisation had significant ($P < 0.05$) effect on soil metabolic quotient at day 126 (Table S2). In general, the CT treatments at this site had higher MBC and MBN than the NT treatments. Soil microbial quotient was also higher in the CT *versus* NT treatments, while metabolic quotient was higher in the NT *versus* CT treatments over the sampling periods, and N fertilised *versus* without N treatments at day 126 (Table 4).

3.5. Management impact on net release of available nitrogen, phosphorus and sulphur

At the Condobolin site, management practices had a significant ($P < 0.05$) effect on net plant available N at day 126, but not at day 30 (Table S1). The CT and PP treatments had significantly higher ($P < 0.05$) net available N than the RT and NT treatments at day 126 (Fig. 3). The net release of available N at this site was 11–23 kg ha^{-1} after 30 days and 15–36 kg ha^{-1} after 126 days across the treatments (Fig. 3). However, at the Merredin site, stubble treatments had a significant effect ($P < 0.05$) on net release of available N only at day 30, but not at day 126 (Table S1). The SR treatment had a significantly higher ($P < 0.05$) net available N than the SB treatment at day 30 (Fig. 4). Across these two stubble treatments, 11–17 kg ha^{-1} and 44–49 kg ha^{-1} of net plant available N were released from the Luvisol at Merredin after 30 and 126 days, respectively (Fig. 4). At the Hermitage site, there was a significant ($P < 0.05$) interactive effect of the management practices (tillage, stubble and fertiliser) on the net availability of N at day 30 but not at day 126 (Table S2). The CT-SR-90N treatment had significantly ($P < 0.05$) higher net available N than the other treatments at day 30 (Fig. 5). The net release of available N in the Vertisol ranged from 4 to 14 kg ha^{-1} after 30 days and 12 to 24 kg ha^{-1} after 126 days of incubation (Fig. 5).

At the Condobolin site, management practices had a significant ($P < 0.01$) effect on the net available P at 126 days, but not at 30 days (Fig. 3, Table S1). At day 30, the net release of available P was 10–22 kg ha^{-1} in the Luvisol at Condobolin (Fig. 3), which decreased at day 126, ranging between 4 and −31 kg ha^{-1} across all the management practices. The RT treatment had higher ($P < 0.01$) net P immobilisation/fixation than the CT, NT and PP treatments at day 126 (Fig. 3). At Merredin, stubble management had no effect on net available P during the incubation period (Table 1). At day 30, the net release of plant available P was 6–16 kg ha^{-1} in the Luvisol at Merredin, which decreased, with values ranging between 5 and −3.8 kg ha^{-1}, at day 126 (Fig. 4). At Hermitage, only tillage practices had a significant ($P < 0.01$) effect on net available P over the study period (Table S2). The net release of available P ranged from 16 to 74 kg ha^{-1} across all

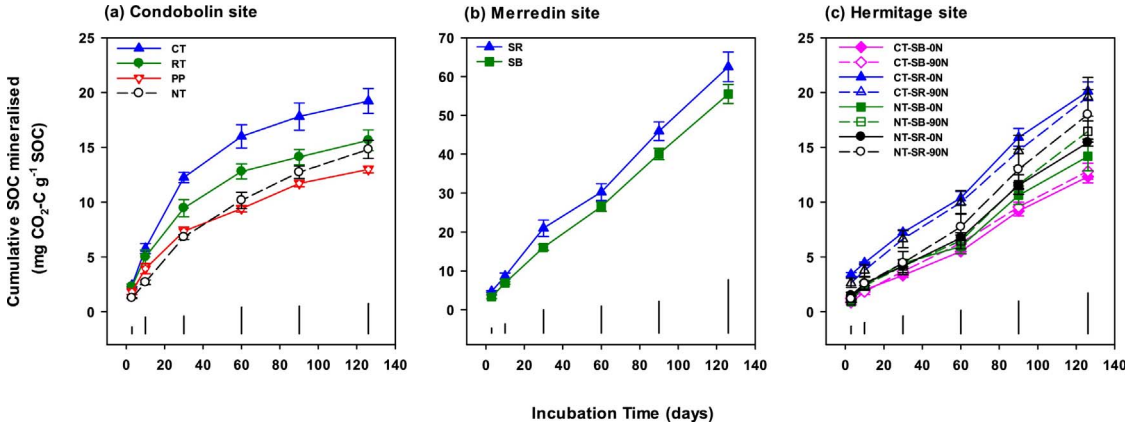

Fig. 2. Impact of contrasting management practices on the relative amount of soil organic carbon mineralised (mg CO_2-C g^{-1} SOC) over 126 days from incubated soils collected (0–10 cm depth) from long-term experimental sites at (a) Condobolin (New South Wales), (b) Merredin (Western Australia), and (c) Hermitage (Queensland). Legends: conventional tillage (CT), reduced tillage (RT), no-till (NT) and perennial pasture (PP) treatments at the Condobolin site; stubble retained (SR) and stubble burnt (SB) treatments at the Merredin site; and factorial combinations of CT, NT, SR, SB, no urea-N (0N) and 90 kg urea-N ha^{-1} yr^{-1} (90N) at the Hermitage site. See further details of the treatments in Methods. Error bars represent ± standard error of the means (n = 3). Vertical black bars show least significance differences ($LSD_{0.05}$) among treatment combinations at each time point.

Table 3
Mean residence time of labile and recalcitrant pools of soil organic carbon (C) and their proportions (%) in the Luvisol and Vertisol (0–10 cm) estimated using a two–pool exponential model fitted to the cumulative soil-C mineralized over 126 days. The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

Mean residence time[a]			
Treatments	Labile C (day)	Recalcitrant C (years)	Labile C/%
Condobolin (Luvisol)			
CT	17.2	48.4	1.31
RT	15.6	56.3	0.96
NT	33.8	61.8	0.93
PP	19.9	74.3	0.84
$LSD_{0.05}$	8.3	5.9	0.34
Merredin (Luvisol)			
SR	4.2	6.1	0.56
SB	4.4	6.7	0.32
$LSD_{0.05}$	3.6	1.5	0.23
Hermitage (Vertisol)			
CT-SB-0N	0.56	30.5	0.08
CT-SB-90N	3.47	29.8	0.09
CT-SR-0N	2.16	20.5	0.32
CT-SR-90N	0.93	20.3	0.23
NT-SB-0N	1.18	27.0	0.10
NT-SB-90N	1.30	22.4	0.05
NT-SR-0N	0.75	24.2	0.10
NT-SR-90N	0.90	20.9	0.07
$LSD_{0.05}$	1.60	6.0	0.09

CT = conventional tillage; RT = reduced tillage; NT = no-till; PP = perennial pasture; SR = stubble retention; SB = stubble burnt; 0N = 0 kg urea-N ha^{-1}; 90N = 90 kg urea-N ha^{-1}.

[a] The mean residence time is the inverse (1/kL or 1/kR) of the mineralisation rate constant. R^2 = 0.99.

Table 4
Management impact on microbial biomass C (MBC), microbial biomass N (MBN), metabolic quotient and microbial quotient in Luvisol and Vertisol (0–10 cm). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

Treatments	MBC (mg kg^{-1})		MBN (mg kg^{-1})		Metabolic quotient (µg CO_2-C mg^{-1} MBC h^{-1})		Microbial quotient (mg MBC g^{-1} SOC)	
	Day 10	Day 126	Day 10	Day 126	Day 10	Day 126	Day 10	Day 126
Condobolin (Luvisol)								
CT	180.8	125.4	35.9	24.2	1.45	0.18	10.8	7.5
RT	208.7	167.0	33.1	26.5	1.066	0.15	12.5	10.0
NT	128.5	102.8	24.6	19.7	0.86	0.16	7.8	6.2
PP	237.2	189.8	43.7	35.0	0.74	0.11	13.2	10.5
$LDS_{0.05}$	31.9	27.5	12.7	9.7	0.25	0.06	4.5	3.6
Merredin (Luvisol)								
SR	231.8	185.4	31.6	25.2	0.93	0.91	20.6	16.5
SB	225.5	180.4	31.7	25.4	0.81	0.85	20.9	16.7
$LDS_{0.05}$	44.6	35.7	15.9	12.7	0.61	0.35	6.4	5.1
Hermitage (Vertisol)								
CT-SB-0N	304.1	243.2	27.0	21.6	0.29	0.35	14.5	11.6
CT-SB-90N	323.1	258.5	26.1	20.9	0.38	0.37	14.4	11.5
CT-SR-0N	326.9	261.5	33.5	26.8	0.38	0.44	15.8	12.6
CT-SR-90N	337.0	269.6	33.0	26.4	0.42	0.53	15.1	12.1
NT-SB-0N	232.7	186.2	25.7	20.6	0.76	0.42	11.5	9.2
NT-SB-90N	262.4	209.0	24.2	19.4	0.70	0.58	11.4	9.1
NT-SR-0N	288.3	230.6	23.6	18.9	0.47	0.39	14.0	11.2
NT-SR-90N	231.8	186.2	16.8	13.5	0.70	0.64	10.8	8.6
$LDS_{0.05}$	44.8	35.8	4.8	3.8	0.24	0.13	2.7	2.1

CT = conventional tillage; RT = reduced tillage; NT = no-till; PP = perennial pasture; SR = stubble retention; SB = stubble burnt; 0N = 0 kg urea-N ha^{-1}; 90N = 90 kg urea-N ha^{-1}.

the treatments in the Vertisol at 30 days after incubation, with the CT had higher net P mineralisation than NT (Fig. 5). However, at 126 days, the net available P decreased to negative values, ranging between −13 and −101 kg ha^{-1}, and the CT caused higher net P immobilisation/fixation at day 126 than the NT treatment (Fig. 5).

At Condobolin, CT released more plant available S than NT and PP during the incubation period (Table S1; $P < 0.05$). At Merredin, stubble retention released more plant available S than SB after 30 days only (Table S1; $P < 0.05$). At Hermitage, only stubble management had a significant ($P < 0.01$) effect on the net available S at day 30, with SB immobilising more plant available S than all SR treatments. However, after 126 days, only tillage showed a significant ($P < 0.01$) effect on net immobilisation of plant available S (Table S2), with all NT treatments immobilising more plant available S than the CT treatments at Hermitage. Net available S in the Luvisol ranged from (a) 5 to 22 kg ha^{-1} at Condobolin, and (b) −4 to 11 kg ha^{-1} at Merredin after 30 days of incubation across all the treatments, which was followed by either small immobilisation or only a slight release of plant available S after 126 days (Figs. 3, 4 and S1). At Hermitage, the net release of plant available S ranged between 12 and −20 kg ha^{-1} over the incubation period across all the treatments (Figs. 5 and S1).

As the bulk density across the treatment at Condobolin were different, when comparing stocks and net nutrient availability on a minimum equivalent soil mass basis, the values in the NT and PP treatments will be ~7–13% lower than the reported values in this study.

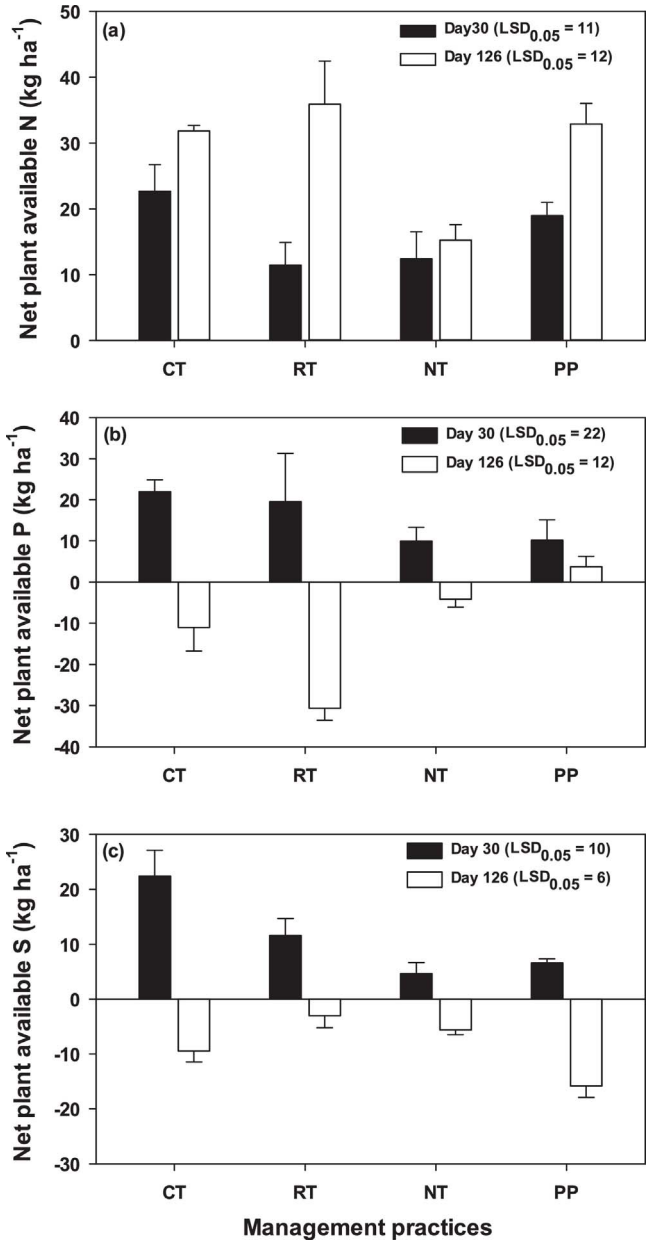

Fig. 3. Impact of contrasting management practices on net release of plant available (a) N, (b) P and (c) S over 30 days (dark bars) and 126 days (white bars) of laboratory incubation at the Condobolin site (New South Wales) as affected by conventional tillage (CT), reduced tillage (RT), no-till (NT) and perennial pasture (PP) treatments. See further details of the treatments in Methods. Error bars represent ± standard error of the means (n = 3). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

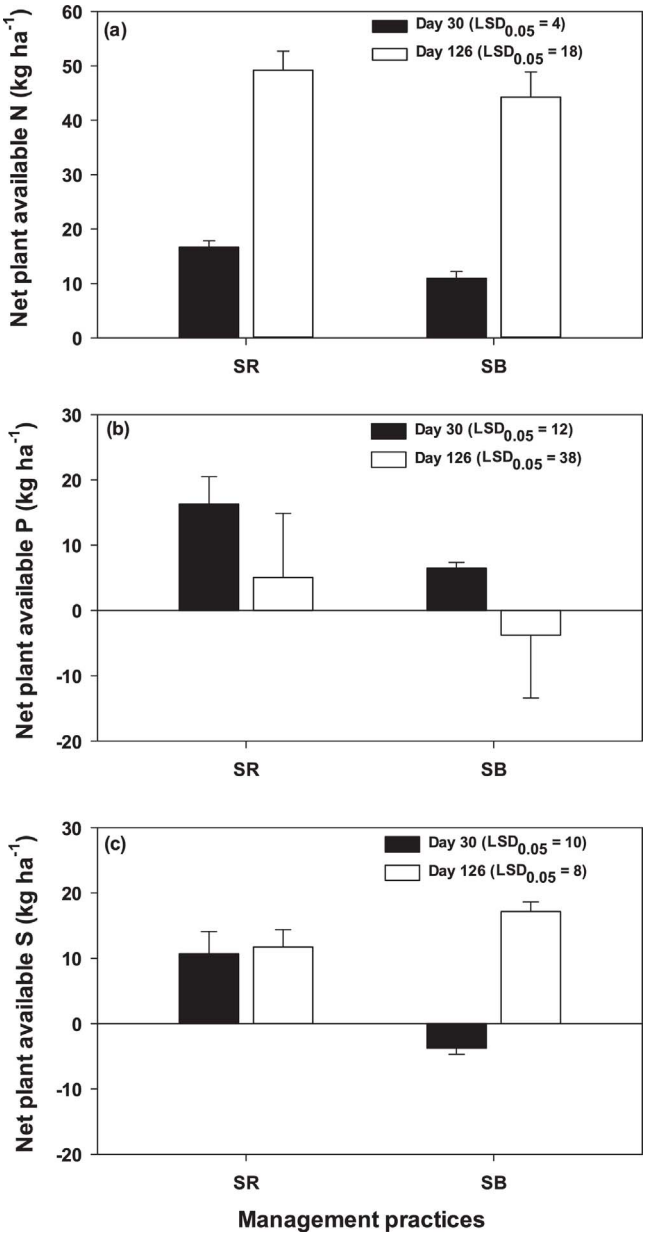

Fig. 4. Impact of contrasting management practices on net release of plant available (a) N, (b) P and (c) S over 30 days (dark bars) and 126 days (white bars) of laboratory incubation at the Merredin site (Western Australia) as affected by stubble retained (SR) and stubble burnt (SB) treatments. See further details of the treatments in Methods. Error bars represent ± standard error of the means (n = 3). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

3.6. Relations between soil properties and carbon–nutrient mineralisation

Across the three sites, there was little correlation between soil properties (total C and nutrient concentrations, clay content, pH, and exchangeable cations) and C mineralisation or nutrient supply over 30 and 126 days (Figs. S4 and S5).

4. Discussion

Although the contrasting management treatments and systems across the three climatic regions and soil types in Australia were not designed as an integrated experiment, these systems represented different long-term soil disturbances (such as CT or RT *versus* NT or PP), or organic matter inputs (such as SR *versus* SB), or N fertilisation. Further, the lack of strong relations between soil properties and SOC–nutrient mineralisation may have been due to variations in the management practices, such as tillage intensity, crop rotation and diversity, and management history across the experimental sites (Figs. S4 and S5). Nevertheless, the selected treatments and systems were important and necessary to understand their legacy effects on soil microbial biomass, activity and organic matter accessibility, with influence on SOC mineralisation and the nutrient supply potential of SOM − a key resource to support soil functions and plant productivity.

4.1. Soil organic carbon mineralisation

Our results showed that at Condobolin, tillage (CT and RT) caused higher SOC mineralisation than the relatively less disturbed system (NT) and undisturbed system (PP) over the study period (Figs. 1 a and

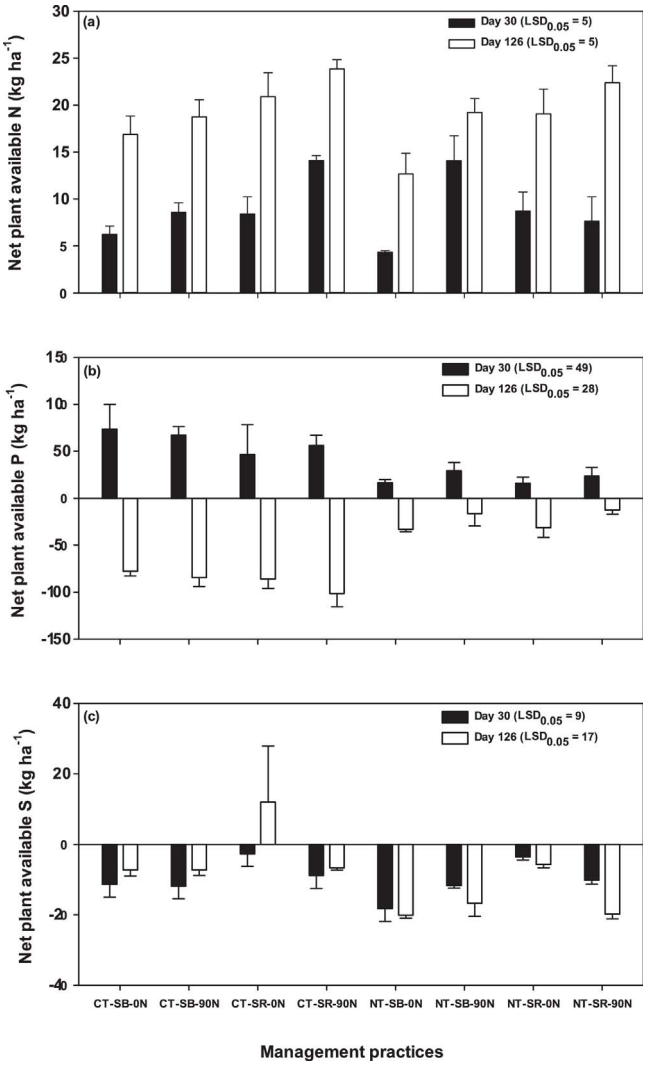

Fig. 5. Impact of contrasting management practices on net release of plant available (a) N, (b) P and (c) S over 30 days (dark bars) and 126 days (white bars) of laboratory incubation at the Hermitage site (Queensland), as affected by conventional tillage (CT), no tillage (NT), stubble retained (SR), stubble burnt (SB), no urea-N (0N) and 90 kg urea-N ha^{-1} yr^{-1} (90N) designed in factorial combinations at the site. See further details of the treatments in Methods. Error bars represent ± standard error of the means (n = 3). The least significant differences ($LSD_{0.05}$) are at 5% level of significance.

S1). Similarly, at Hermitage, the CT-SR with 90N treatment showed higher decomposition of SOM and evolution of CO_2-C from the soil relative to the other treatments (Figs. 1 c, 2 c and S1). This study also found higher soil microbial biomass and activity under differently managed tillage (CT and/or RT) *versus* no-till (NT) systems at both field sites (Table 4). These results prove the well-established paradigms that tillage exposes SOM, bringing the soil microbial population in direct contact with the organic material in soil, therefore, mineralisation of SOM occurred more rapidly than the less disturbed (NT) and undisturbed (PP) systems (Raiesi et al., 2006). Moreover, differences in the availability of labile C (such as *via* stubble incorporation through tillage at Condobolin and Hermitage), and inorganic N fertilisation (at Hermitage) into the systems might have also stimulated the growth of soil microbial population to enhance SOM decomposition (Chen et al., 2014). These results agree with findings from various long-term tillage studies, that soil disturbance increased the decomposition of SOM in surface layers due to higher microbial biomass and activity (Dalal and Chan, 2001), which in turn increase nutrient cycling (Bimüller et al., 2016). Further, at Condobolin, the higher soil MBC and MBN in the PP were likely due to continuous C input into the system *versus* the cropping systems (Kuzyakov and Domanski, 2000), however, SOC mineralisation rate per unit of MBC was lower in the PP than the CT and RT treatments (Table 4). At the Merredin site, the SOC mineralisation rate was significantly ($p < 0.05$) higher in the SR than SB during the first 3 days, similar to the SR treatments at Hermitage (Fig. S1). However, the cumulative CO_2-C released over 126 days was only significant at $p < 0.1$ across the treatments (Fig. 2b). The possible reason could be the similar levels of SOC and total nutrient (N, P and S) concentrations, and soil MBC, MBN and microbial quotient in both of the treatments at Merredin over the study period (Tables 2 and 4). Our study also observed that the estimated MRT of SOC was longer (62–74 years) in the NT and PP treatments than the CT or RT treatments (48–56 years) at Condobolin (Table 3), confirming that NT or PP may have enhanced the protection of SOM within soil aggregates and deceased microbial accessibility to SOM (Six et al., 2000). However, at Hermitage, the estimated MRT of SOC was not impacted by tillage practices, but was shorter (20–24 years) in the SR than the SB treatments (22–30 years) (Table 3). This result confirmed that the SOC mineralisation by microorganisms may have been enhanced (*via* "co-metabolism") due to the presence of relatively more labile residue C in the SR *versus* SB. Further, the relatively lower metabolic quotient and higher microbial quotient values on day 10 in the CT *versus* the NT treatments indicate that microbes were efficiently decomposing SOM to support their growth (Rui et al., 2016) (Table 4). However, compared with the SR and SB treatments at Hermitage, the estimated MRT of SOC at the Merredin site was similar across the SR and SB treatments. This result was likely due to a similar level of short-term SOC mineralisation in both treatments (Tables 3 and 4). However, a long-term mineralisation study may provide realistic values of the MRT (Singh et al., 2012), possibly because microbes may decompose SOM with different efficiencies in the SR and SB treatments after decomposition of labile C components. Hoyle and Murphy (2006) previously studied changes in microbial functions and diversity in stubble retention *versus* burnt treatments at Merredin. While they reported no difference in total SOC between treatments at any depth, both MBC and labile C pools measured under stubble retained treatments were significantly higher than in the stubble burnt treatments at 0–5 cm depth. Treatment differences beyond this depth of sampling were not evident at this site. Our study also found significantly higher dry mean weight diameter (DMWD) and wet mean weight diameter (WMWD) (indicators of soil structure stability; Devine et al., 2014) in the NT and PP *versus* CT and RT at Condobolin (Table S3), and higher WMWD in the direct drilled SR than SB at Merredin. These results might be related to the effect of less or no soil disturbance in the NT and PP at Condobolin, and in the SR at Merredin, which might have facilitated greater formation of large *versus* small sized aggregates in the Luvisols at both sites. However, in the Vertisol, the high smectite clay might have overridden the tillage and stubble management effects, and therefore showed similar soil structure stability across the management practices (Table S3).

4.2. Mineralisation of nitrogen

Consistent with SOC mineralised (Figs. 1 and 2), our study showed that the CT, SR and/or N fertilised systems significantly increased the release of plant available N (mostly in NO_3^--N form; Fig. S3) following SOM decomposition during the incubation (Figs. 3–5 and S2). The highest net N mineralisation occurred in the CT and/or RT *versus* NT and PP at Condobolin, probably due to fact that tillage, although done every two years in the 5-year crop–pasture rotation (see Methods), would be exposing aggregate-protected SOM to microbial decomposition (Six et al., 2000), thus resulting in higher N mineralisation. This result is in agreement with Pandey et al. (2010), who reported that CT *versus* NT has the potential to increase soil N mineralisation. Studies also reported that tillage enhances soil microbial biomass and activity, possibly *via* enhanced soil C availability and soil porosity and aeration (Carter et al., 1994; Raiesi, 2006), consequently stimulating soil N

mineralisation (Raiesi, 2006). Similarly, at the Hermitage site, the CT-SR with 90N showed higher net N mineralisation (*cf*. other treatments), which would be due to the continuous tillage effect, possibly further supported by labile C input from retained crop stubble and N input from urea application. Our study also observed that the CT *versus* NT had higher MBC and MBN, and lower microbial C:N ratio and metabolic quotient, suggesting dominance of fungal relative to bacterial communities across the NT treatments, thus causing lower N mineralisation than the CT treatments (Table 4) (Strickland and Rousk, 2010). Interestingly, Raiesi (2006) reported that tillage along with residue incorporation can significantly increase N mineralisation compared to NT possibly *via* stimulating SOM mineralisation, and can release 12–19 mg N g^{-1} soil N over 60 days of incubation. Similarly, Hoyle and Murphy (2011) also reported that soil disturbance and residue incorporation can enhance the magnitude of inorganic N release in a soil. During the incubation periods, the current study found that the extractable NH_4^+-N at all the three sites was lower than the extractable NO_3^--N (Fig. S3). At day 0, NH_4^+-N comprised 14–56% of the total extractable N and thereafter the NH_4^+-N concentration rapidly decreased, falling to 0.3–3% of the total extractable N across all the sites (Fig. S3). The lower extractable NH_4^+-N *cf*. NO_3^--N from all the treatments during the incubation period was due to continuous oxidation of NH_4^+-N to NO_3^--N and NO_2^--N, possibly supported by high abundance of nitrifying bacteria during aerobic incubation (Pandey et al., 2010). Our result showed that the net release of plant available N in the Vertisol was relatively lower (Figs. 3–5), although the water filled pore space was higher (see Methods), than in the Luvisols. The possible reason could be the higher clay content (63%) (Table 1) and larger specific surface area of smectitic clay (Wattel-Koekkoek et al., 2001), thus possibly favouring greater sorption of SOM and mineral N in the Vertisol, relative to the Luvisols (with ~26% clay) (Christensen, 2001; von Lützow et al., 2007; Saidy et al., 2013).

4.3. Mineralisation of phosphorus and sulphur

Our study showed a net positive release of plant available P after the first 30 days, which with time was immobilised across all treatments and soil types (Figs. 3–5 and S2). The CT *versus* RT, NT and PP at Condobolin, SR *versus* SB at Merredin and the CT-SR/SB with 90N treatments compared to other treatments at Hermitage increased the net release of available P over 30 days (Figs. 3–5). The net release of plant available (Colwell) P from soils across all the sites and management practices in the first 30 days might be due to the substantial amount of organic P in soil that was taken up by microbes and released back to soil after microbial degradation with minimal sorption on soil minerals. Also, Damon et al. (2014) reported that in the short term, net mineralisation of P can occur in soil. However, after 126 days, we observed net immobilisation of plant available P across all field sites (Figs. 3–5, S1). Possible reasons for the observed net P immobilisation could be related to decreased availability of easily decomposable C compounds due to their continuous utilisation by microbial biomass, which can otherwise compete with P sorption sites, and particularly when there is a lack of plant C input (as in this incubation study) (Chen et al., 2014). Consequently, there could be increased sorption of P on clay surfaces, cation bridging of P with Fe, Al and Ca hydroxides on clay minerals (Table 1) (Guppy et al., 2005; Duputel et al., 2013), and/or precipitation of P by polyvalent cations in the soils (Jones et al., 2015). There could also be the use of P released from the ongoing mineralisation of SOM by microbes for their enzyme synthesis (Malik et al., 2012). Clay minerology also plays a significant role in P adsorption. For example, smectitic clay has greater anion sorption capacity *via* cation bridging than kaolinitic clay (Saidy et al., 2013), thus resulting in relatively higher P immobilisation/fixation (i.e. net negative P availability) in the Vertisol than Luvisol, as observed in the current study.

To our knowledge, few studies have focused on the impact of long-term agricultural management on the S mineralisation potential of SOM in different soils (Kopittke et al., 2016a). Our study found that the farming systems, including crop–pasture, tillage and/or stubble management influenced the release of plant available S, and the effect varied in different soils. For example, our study found a net release of available S in the Luvisol at Condobolin, *i.e.* 5–22 kg S ha^{-1} over 30 days across the management practices (Fig. 3). The net available S was higher in the relatively disturbed systems (such as CT/RT *versus* NT/PP), likely due to greater microbial activity and exposure of SOM to decomposition after periodic aggregate destabilisation, which may decrease total S concentration with time (Bhupinderpal-Singh et al., 2004; Kopittke et al., 2016a). Consistently, our data showed lower aggregate stability and higher metabolic quotient in CT/RT than NT/PP (Table 4 and S3). However, over 126 days, any S released from SOM or microbial degradation was locked up by either microbes or clay minerals (Eriksen, 2005; Keiluweit et al., 2015). Further, the current study found a higher net plant available S in the SR than SB on day 30 in the Luvisol at Merredin (Fig. 4). Interestingly, the metabolic quotient, which is an indicator of microbial activity, remained high throughout (*i.e.* did not decrease with time) in both SR and SB treatments (Table 4), which may have favoured priming of native SOM (Kuzyakov, 2000) to cause a further release of plant available S in both the treatments. However, there was a net S immobilisation throughout the study period in the Vertisol across all the management practices (Fig. 5). The immobilisation of plant available S during the incubation period might be related to (i) low S stocks in the Vertisol (0.16–0.23 t ha^{-1}), *e.g.* when compared with Luvisol (0.26–0.30 t ha^{-1}) (Table 2), which could not meet S requirement of microbes and therefore immobilised all available S (Eriksen et al., 1995); (ii) like P immobilisation, S may also be sorbed by clay minerals; and/or (iii) precipitation of SO_4^{2-} with metal cations (such as Fe, Al or Ca) in the soil (Table 1) (Keiluweit et al., 2015). Compared with P immobilisation, the S immobilisation was lower across all the treatments (Figs. 3–5, S1) suggesting that phosphate may displace or reduce sulphate adsorption by clay minerals (Metson and Blakemore, 1978). Although our study found immobilisation of P and S with increasing incubation time (Figs. 3–5), the nutrients released through SOM mineralisation may be readily available for uptake by growing plants under field conditions.

5. Conclusions

Our study demonstrated that SOM has a fertiliser value in terms of N, P and S supply to support crop productivity. In particular, tillage, stubble retention and/or N fertilisation enhanced SOC mineralisation and the release of plant available nutrients in soils. The results showed that available N was continuously released during SOM decomposition in the soils (Luvisols and Vertisol) during the incubation period (126 days), while considerable quantities of available P and S were released in the Luvisols, and P (not S) in the Vertisol, over a 30 day period. Our nutrient availability data therefore suggests that the short term release of nutrients (particularly P and S) could be subsequently locked up in the soils over the long-term (such as during a fallow period), possibly *via* microbial immobilisation or chemical sorption on soil minerals. In summary, the current study supported the paradigms that management systems with greater soil disturbance along with organic matter input can promote SOM mineralisation and release of plant available nutrients in the soils. Thus, there could be a trade-off between enhancing SOM mineralisation and nutrient release *via* tillage, to support plant growth, *versus* increasing their storage in less disturbed systems, which could further vary with soil types and climatic conditions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2017.08.005.

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