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Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems

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Abstract

Chemical and physical degradation of Red Ferrosols in eastern Australia is a major issue necessitating the development of more sustainable cropping systems. This paper derives critical concentrations of the active (permanganate-oxidisable) fraction of soil organic matter (C1) which maximise soil water recharge and minimise the likelihood of surface runoff in these soils.

Ferrosol soils were collected from commercial properties in both north and south Queensland, while additional data were made available from a similar collection of Tasmanian Ferrosols. Sites represented a range of management histories, from grazed and ungrazed grass pastures to continuously cropped soil under various tillage systems. The concentration of both total carbon (C) and C1 varied among regions and farming systems.

C1 was the primary factor controlling aggregate breakdown, measured by the percentage of aggregates $<0 \cdot 125$ mm (P125) in the surface crust after simulated rainfall. The rates of change in P125 per unit change in C1 were not significantly different ($P < 0 \cdot 05$) for soils from the different localities. However, soils from the coastal Burnett (south-east Queensland) always produced lower P125 (i.e. less aggregate breakdown) than did soils from the inland Burnett and north Queensland locations given the same concentration of C1. This difference was not associated with a particular land use.

The 'critical' concentrations of C1 for each region were taken as the C1 concentrations that would allow an infiltration rate greater than or equal to the intensity of a 1 in 1 or 1 in 10 year frequency rainfall event of 30 min duration. This analysis also provided an indication of the risk associated with the concentrations of C1 currently characterising each farming system in each rainfall environment. None of the conventionally tilled Queensland Ferrosols contained sufficient C1 to cope with rainfall events expected to occur with a 1 in 10 frequency, while in many situations the C1 concentration was sufficiently low that runoff events would be expected on an annual basis.

Our data suggest that management practices designed both to maximise C inputs and to maintain a high proportion of active C should be seen as essential steps towards developing a more sustainable cropping system.

Additional keywords: Ferrosols, Oxisols, organic carbon, permanganate fractions, aggregate stability, infiltration, erosion risk.

Introduction

Red Ferrosols (Isbell 1993) derived from basic volcanic rocks such as basalt have long been valued in eastern Australia due to their favourable physical

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properties and initially moderate to high nutrient status. They are used for a wide range of agricultural and horticultural cropping systems and for intensive pasture production. Most broadacre crop production on Ferrosols is rain-fed, whereas the more intensive production systems (e.g. potato, dairy pasture) are irrigated or in higher rainfall environments. Agricultural production on these soils has caused a decline in their chemical and physical fertility (Bridge and Bell 1994; Moody 1994) and to maintain productivity, more sustainable cropping systems must be developed. The crucial role that soil organic matter plays in the fertility of Ferrosols has been documented (Moody 1994; Oades 1995), and it is apparent that the level of sustainability of any production system on Ferrosols will depend on its impact on the level of soil organic matter.

The easily oxidisable ('active') fraction of soil organic matter has been shown to be well correlated with key soil chemical [pH buffer capacity and effective cation exchange capacity (ECEC)] and physical (aggregate stability under rain) properties of Ferrosols (Moody *et al*. 1997; Bell *et al*. 1998*a*). It has also been shown to be a better indicator of these properties than total organic carbon (C). Intensive nutrient management practices can moderate the impact of declining soil organic matter levels on soil chemical fertility and crop productivity on Ferrosols (Bell *et al*. 1998*b*). However, if the soil's infiltration rate is low relative to the intensity of incident rain, then recharge of stored soil water will be restricted and loss of fertile surface soil through erosion will be enhanced. As a result, Cotching and Wright (1994) suggested that accelerated soil erosion by water in areas of intensive land use was the most pressing issue for sustainable management of krasnozem (Red Ferrosol) soils. We have therefore considered the capacity of the soil to allow rainfall to infiltrate to be the most critical factor determining sustainable agricultural production on Ferrosols.

There have been attempts to determine the relative sustainability of different farming systems by comparing the proportions of the total soil organic C in an active fraction (the Carbon Management Index of Blair *et al*. 1995). However, such indices cannot be used to quantify properties other than soil C and are therefore of little benefit in assessing the impact of changed management practices. The aim of this paper is to derive 'critical' levels of active soil organic matter for Ferrosols in different localities in eastern Australia, such that the risks of surface runoff and erosion are minimised and rainfall use efficiency is improved. The current levels of active soil organic matter in existing farming systems are examined relative to these critical levels.

Materials and methods

Site details

Ferrosol soils were collected from commercial properties in the inland and coastal Burnett regions of south-east Queensland and the Atherton Tableland and Lakeland Downs regions of north Queensland. In addition, data were made available from a collection of Ferrosols from northern Tasmania (Table 1; L. A. Sparrow 1998, pers. comm.). Sites represented a range of management histories, from grazed and ungrazed grass pastures to continuously cropped soil under conventional and no-till management systems (Table 2).

Rainfall infiltration, aggregate stability, and soil organic carbon

Methods of determination of laboratory rainfall infiltration rate and aggregate stability were described in detail in Bell *et al*. (1998*a*). Briefly, bulked samples of air-dried surface soil (0–10 cm depth) were crumbled by hand before being loosely packed into trays (30 cm by 30 cm by 20 cm deep). High intensity, simulated rainfall was applied to these samples at a rate of 100 mm/h for 30 min. The rainfall energy applied to the unprotected soil surface was equivalent to 29 $J/m^2 \cdot mm$. The infiltration rate during the final 5 min of the rainfall period (FIR) was recorded for each tray. In addition, samples were collected from the surface 5 mm of each tray after rain and analysed for aggregate size distribution using a modified Yoder wet sieving apparatus (Loch 1995). Aggregate sizes ranging from >2 mm diameter to <0·125 mm diameter were collected and weighed. The percentages by weight of aggregates <0·125 mm in diameter (P125) were determined and related to FIR.

Table 1. Mean and range (in parentheses) of clay content, total C, and the C1 fraction for Ferrosols (0–10 cm) from selected localities in eastern Australia

Locality	No. of sites	Clay (%)	Total C (g/kg)	C1 (g/kg)
Northern Tasmania	27	n.d.	56·1 (29·0–87·6)	4·24 (2·30–6·48)
Inland Burnett	89	63 (57–67)	20·4 (12·4–52·7)	1·66 (0·89–5·01)
Coastal Burnett	21	62 (53–70)	19·3 (12·7–39·6)	1·47 (0·76–3·57)
Atherton Tableland	21	65 (59–71)	19·8 (12·1–30·1)	1·34 (0·89–2·04)
Lakeland Downs	14	60 (40–67)	21·9 (12·6–33·2)	1·91 (1·25–3·09)

n.d., not determined.

Table 2. Numbers of samples (n), means, and 95% confidence limits (in parentheses) of total C and C1 in Ferrosols (0–10 cm) under different Ferrosol farming systems in Queensland

CT, conventional tillage; ZT, zero tillage

Farming system	n	Total C (g/kg)	C1 (g/kg)
Inland Burnett			
Broadacre continuous cropping: CT	38	17·8 (±7·4)	1·37 (±0·55)
Broadacre continuous cropping: ZT	8	17·8 (±7·3)	1·43 (±0·51)
Broadacre cropping after pasture ley: CT	24	20·9 (±14·4)	1·77 (±1·26)
Broadacre cropping after pasture ley: ZT	8	25·4 (±8·1)	2·25 (±0·99)
Grass pasture	11	23·1 (±27·7)	2·02 (±2·81)
Coastal Burnett			
Sugarcane: trash burnt	8	17·8 (±14·1)	1·33 (±1·15)
Sugarcane: trash retained	6	17·2 (±4·7)	1·25 (±0·45)
Intensive vegetables	3	15·2 (±6·4)	1·05 (±0·79)
Horticultural tree crops	2	19·4 (±4·8)	1·43 (±0·15)
Grass pasture	2	37·9 (±5·7)	3·36 (±0·69)
Atherton Tableland			
Broadacre cropping: CT	15	18·7 (±11·5)	1·21 (±0·55)
Broadacre cropping after pasture ley: CT	6	22·3 (±12·9)	1·66 (±0·78)
Lakeland Downs			
Broadacre cropping: CT	10	19·3 (±7·7)	1·61 (±0·52)
Grass pasture	4	28·3 (±11·7)	2·68 (±1·05)

Samples for chemical analyses were oven-dried (40°C) and ground to <0·125 mm for C analysis or <2 mm for other chemical analyses. Total C was determined by combustion in a Leco furnace, while the active C fraction (C1) was determined as the amount of C oxidised by 33 mM $KMnO_4$ (Blair *et al*. 1995). Other soil chemical analyses were undertaken using methods described by Rayment and Higginson (1992). Briefly, soil pH was determined in a

1 : 5 soil : water suspension, exchangeable cations were extracted with 1 M NH_4Cl (pH 7·0), and ECEC was determined from the sum of exchangeable cations and 1 M KCl extractable acidity. Soil chemical properties other than total C and C1 have been presented elsewhere (Bell *et al.* 1998*a*).

Regional rainfall statistics

Data describing the rainfall characteristics (frequency, intensity, and duration) of selected sites from eastern Australia were obtained from the I-F-D Design Rainfall Program (WP Software 1988). The following sites were chosen to represent the range of major Ferrosol cropping areas in eastern Australia: Ulverstone (northern Tasmania); Moe and Ballarat (Victoria); Dorrigo and Grafton (northern New South Wales); Kingaroy, Gayndah, Childers and Bundaberg (southern Queensland); and Innisfail, Atherton, Mareeba, and Lakeland Downs (north Queensland).

Each simulated rainfall event in the laboratory used to determine P125 and FIR consisted of a 30-min rainfall duration, so the I-F-D data for each region were compared on the basis of frequency of occurrence of 30-min rainfall events of varying intensity. This examination indicated that a subset of 6 locations (Ulverstone, Kingaroy, Bundaberg, Atherton, Lakeland Downs, and Innisfail) adequately covered the range of intensity *v.* frequency relationships for the major Ferrosol cropping areas, and these data are presented in Fig. 1. The rainfall data from this subset were used to represent the incident rainfall on Ferrosols in northern Tasmania, the inland and coastal Burnett, Atherton Tableland, Lakeland Downs, and the wet tropical coast of Queensland, respectively.

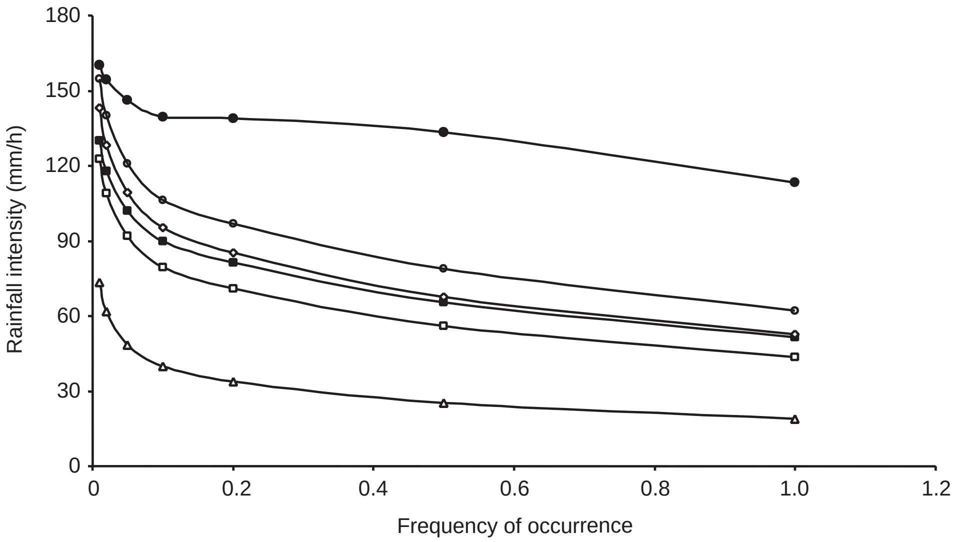

Fig. 1. Intensity of rainfall events of 30 min duration occurring with varying frequency for locations chosen to represent the Ferrosol cropping regions of eastern Australia. The sites are Ulverstone (△), Kingaroy (□), Bundaberg (◇), Innisfail (●), Atherton (■) and Lakeland Downs (○).

Results

Total C and C fractions

There was a wide range in total C and C1 in soil from the various localities, with the northern Tasmanian Ferrosols having notably higher mean concentrations than the Queensland sites (Table 1). All localities showed a 3–4-fold range in both total C and C1 concentrations across the various land managements.

Where data were available, the effects of management on soil organic C were investigated by examining differences between farming systems within localities (Table 2). These data suggest that both farming system *per se*, and management within a farming/tillage system, affect the concentration of both total C and C1. For example, the data from the inland Burnett suggest that a simple change of tillage system (conventional to zero till) on continuously cropped soil has had minimal effect on soil organic C. However, inclusion of pasture leys within the farming system has tended to increase soil organic C, particularly when the ley was returned to cropping using a zero tillage cropping system.

It is also of interest to note the generally higher soil organic C shown by grass pastures in all localities. Organic C levels in pasture soils within regions were often quite variable due to differences in pasture species, pasture duration, and grazing management. However, the advantages relative to continuously cropped soils, and even to the perennial sugarcane (*Saccharum sp.*) and horticultural tree crop systems in the coastal Burnett, were often substantial. The advantage relative to perennial sugarcane was still evident when that crop was grown in trash-retained (green cane trash blanket) systems for at least 10 years, although there was some evidence of an increase in C levels in the surface 2·5 cm under an existing trash blanket before plough-out (data not shown).

Aggregate stability and infiltration of simulated rain

The relationship between FIR and P125 in the surface crust after simulated rain was previously derived for Ferrosols in the inland Burnett (Bell *et al.* 1998*a*). A similar relationship was derived for the Ferrosols of the coastal Burnett, and neither the slope nor the intercept was significantly different ($P > 0{\cdot}05$) from that of the inland Burnett subset. The regression equation describing the pooled data is presented in the following equation:

$$\mathrm{FIR} = 131{\cdot}6(\pm\,4{\cdot}9) - 3{\cdot}71(\pm\,0{\cdot}23) \times \mathrm{P125} \qquad (r^2 = 0{\cdot}81,\ n = 61) \qquad (1)$$

The soil property primarily determining P125 in inland Burnett Ferrosols was previously shown to be C1 (Bell *et al.* 1998*a*). A similar analysis conducted on the data from coastal Burnett Ferrosols also indicated that C1 was the primary determinant of aggregate breakdown, accounting for a significantly greater proportion of the variation in P125 ($r^2 = 0{\cdot}44$) than total C ($r^2 = 0{\cdot}27$). However, whilst the slopes of the regressions describing the relationship between C1 and P125 for the inland and coastal Burnett subsets were not significantly different ($P > 0{\cdot}05$), the intercepts were (Fig. 2). As a result, less C1 would seem to be required to prevent aggregate breakdown and surface crusting in the coastal Burnett soils than in the soils of the inland Burnett.

Derivation of critical C1 concentrations

The intensity of 30-min rainfall events which fall either annually or every 10 years (Fig. 1) was used to define the infiltration capacity required to maximise infiltration and minimise runoff and erosion in each of the key localities (Table 3). The relationships between P125 and FIR (Eqn 1), and between C1 and P125 for the inland and coastal Burnett Ferrosols (Fig. 2), were then used to derive the critical C1 concentrations necessary to cope with rainfall events of those intensities (Table 3). Data presented in Bell *et al.* (1998*a*) showed that similar relationships between field rainfall infiltration rates and C1 were displayed by uncompacted Ferrosols from the inland Burnett, the Atherton Tableland, and Lakeland Downs. As a result, the relationship between C1 and P125 derived for the inland Burnett was used here to calculate critical concentrations of C1 for both north Queensland localities. A similar relationship between C1 and P125 was also used to derive critical concentrations of C1 for the Innisfail and Tasmanian Ferrosols, although this assumption will need to be confirmed in further testing.

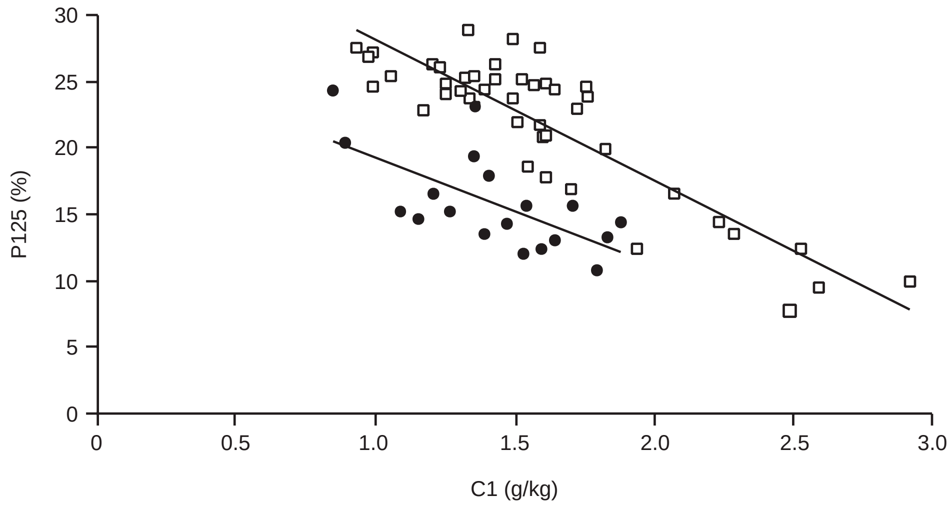

Fig. 2. Relationship between the percentage aggregates $<0 \cdot 125$ mm (P125) in the surface crust after 30 min of simulated, high intensity rain and the concentration of C1 carbon for soils from the inland and coastal Burnett regions of Queensland. The relationship for inland Burnett soils (□) is described by the equation $\mathrm{P125} = -10 \cdot 60\mathrm{C1} + 38 \cdot 7$ ($r^2 = 0 \cdot 77$), while that for coastal Burnett soils (●) is $\mathrm{P125} = -8 \cdot 45\mathrm{C1} + 25 \cdot 8$ ($r^2 = 0 \cdot 44$).

Table 3. Concentration of C1 carbon required to prevent runoff from 30-min rainfall events with frequencies of occurrence of 1 in 1 and 1 in 10 years

Locality	Frequency of occurrence	30-min rainfall intensity (mm/h)	C1 for no runoff (g/kg)
Northern Tasmania	Every year	19	0·79
	1 in 10 years	40	1·32
Inland Burnett	Every year	44	1·42
	1 in 10 years	80	2·34
Coastal Burnett	Every year	53	0·55
	1 in 10 years	95	1·89
Atherton Tableland	Every year	51	1·60
	1 in 10 years	90	2·59
Lakeland Downs	Every year	62	1·88
	1 in 10 years	106	3·00
Innisfail	Every year	113	3·19
	1 in 10 years	139	3·85

The critical concentrations of C1 for each locality (Table 3) were then compared with the concentrations obtained from the 0–10 cm layers in commercial fields under the various farming systems (Tables 1 and 2). This analysis provided an indication of the risks associated with the intrinsic C1 concentration for each farming system in each rainfall environment. The contrasts between localities and farming systems were marked. For example, all of the Tasmanian Ferrosols contained enough C1 to provide sufficient aggregate stability to cope with rainfall events of at least a 1 in 10 frequency. However, none of the conventionally tilled Queensland Ferrosols contained sufficient C1 to cope with rainfall events expected to occur with a similar frequency, while in many situations the C1 concentration was sufficiently low as to expect runoff events on an annual basis.

Discussion

These results provide further confirmation of the very important role played by the active C1 fraction of soil organic matter in determining aggregate stability and rainfall infiltration in Ferrosols. Perhaps more importantly, they illustrate the potential application of C1 as an indicator of the structural stability of Ferrosols in different farming systems. This indicator could be of particular use to agricultural advisers and farm managers wishing to evaluate the potential impact of adoption of new management practices (e.g. zero tillage), especially in relation to the degree of risk posed by local rainfall patterns. For example, our data (Tables 2 and 3) show that building up C1 levels in the soil may have a greater impact in reducing surface crusting and improving rainfall infiltration capacity in rain-fed cropping enterprises in the inland Burnett than simply changing to zero till systems. This could be achieved by use of pasture leys, or large inputs of organic amendments like feedlot manure (Bell *et al*. 1997). Similarly, the relatively low levels of C1 characterising soils under zero till management systems has emphasised the extreme dependence of such systems on maintenance of high levels of surface protection from crop residues.

High levels of erosion risk and inefficient use of incident rainfall were also evident in the current cropping systems of Ferrosols of both the Atherton Tableland and Lakeland Downs (Tables 2 and 3). Our data suggest that management practices designed both to maximise C inputs and to maintain a high proportion of active C should be seen as essential steps towards developing more sustainable cropping systems. However, where rainfall intensities are very high (e.g. the wet tropical coast), or management options are limited by a lack of irrigation, maintenance of soil surface cover by crop canopies (perennial crops or pastures) or crop residues during periods of high erosion risk will be essential.

In contrast, the observed decline in soil organic matter levels in intensive horticultural systems of east Gippsland (Hirst *et al*. 1992) and northern Tasmania (Wright 1987; L. A. Sparrow 1998, pers. comm.) seems less likely to produce high levels of erosion risk and inefficient use of incident rainfall. These changes to soil organic matter status, while undoubtedly producing a decline in aggregate stability, would be unlikely to result in surface seals that were impermeable enough to result in frequent runoff events. Assuming a relationship between P125 and C1 similar to either group of Queensland Ferrosols (Fig. 2), soil from the field with the lowest C1 levels in the Tasmanian data set (2·30 g/kg, Table 1) would support an FIR of 78–108 mm/h. Even the lower estimate either exceeds

(Ulverstone, Fig. 1) or roughly approximates (Moe, Ballarat) the intensity of a rainfall event of 1 in 100 year frequency (Fig. 1: W.P. Software 1988). This analysis would therefore suggest that reduced rainfall infiltration due to subsurface factors like compaction (Bridge and Bell 1994; Cotching and Wright 1994) may be a more important factor than improving soil organic C for minimising erosion in Ferrosols in cropping regions characterised by relatively low rainfall intensity.

The collection of coastal Burnett Ferrosols showed a sensitivity of aggregate stability to variation in C1 concentration similar to the soils of the inland regions (Fig. 2), despite marked differences in geological age and composition (McTaggart 1960; Vandersee and Kent 1983). However, the clear separation evident between coastal and inland soils suggests that an additional factor was contributing significantly to aggregation in the coastal Burnett soils. This factor was unlikely to be associated with the dominant sugarcane cropping system, as sites under quite different land uses (e.g. grass pastures and long-term, perennial horticultural crops) lay on the same P125 *v.* C1 line as soils under sugarcane monoculture. Further chemical analyses showed that this difference in aggregation also could not be accounted for by differences in clay content (Table 1), or by the amounts of oxalate iron, silicon, and aluminium (data not shown), factors often considered to contribute to binding and aggregation (Shainberg 1992; Mullins and Ley 1995). Isbell (1994) noted considerable variation in the reported clay mineralogy of Red Ferrosols of eastern Australia, particularly with regard to amounts of the clay minerals gibbsite, haematite, and goethite. There was also some doubt expressed about the reported occurrence or otherwise of halloysite. Such variation in mineralogy of Ferrosols may explain the underlying aggregate stability differences between the inland and coastal Burnett, and should be explored further.

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