Soil & Tillage Research 178 (2018) 209–223

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Agricultural management practices impacted carbon and nutrient concentrations in soil aggregates, with minimal influence on aggregate stability and total carbon and nutrient stocks in contrasting soils

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ARTICLE INFO

Keywords:
Tillage
Stubble
Aggregate-size distribution
Farming system
Soil organic carbon
Luvisol
Vertisol

ABSTRACT

Agricultural management practices can affect soil structure and soil organic carbon (SOC) and nutrient stocks, which are important for sustainable agriculture. There is however limited understanding of the long-term impact of management practices on SOC and total nitrogen (N), sulphur (S) and phosphorus (P) concentrations in aggregates from different soils, and consequent effects on SOC and nutrient storage in agro-ecosystems. Soils from long-term (16–46 years) management systems in semi-arid (Luvisol, at Condobolin, NSW), Mediterranean (Luvisol, at Merredin, WA) and sub-tropical (Vertisol, at Hermitage, QLD) environments in Australia were collected from 0 to 10 cm, 10 to 20 cm and 20 to 30 cm depths. Dry- and wet-sieving techniques were used to fractionate the soils into mega-aggregates (> 2 mm), macro-aggregates (2–0.25 mm), micro-aggregates (0.25–0.053 mm), and silt-plus-clay particles, including micro-structures (< 0.053 mm) *i.e.* "silt-plus-clay fractions". Management practices in the Luvisols comprised conventional (CT) and reduced tillage (RT) under mixed crop–pasture rotation, no-till (NT) under continuous cereal–cover crop rotation, and perennial pasture (PP) at Condobolin, and stubble either retained (SR) or burnt (SB) under direct-drilled continuous wheat–legume rotation at Merredin. The practices in the Vertisol comprised a factorial combination of CT, NT, SR, SB, with either 0 (0N) or 90 kg urea-N ha^{-1} (90N) under continuous wheat–wheat rotation.

In the Luvisol at Condobolin, the PP and NT had significantly ($p < 0.05$) higher soil aggregate stability than the CT and RT, with no impacts of management on SOC and total N, S and P stocks at all depths. The practices in the Luvisol at Merredin and Vertisol at Hermitage had no impact on soil aggregate stability, or on SOC and nutrient stocks at all depths, except the NT-SR-90N at Hermitage showed higher SOC ($p < 0.10$) and nutrient ($p < 0.05$) stocks than the other treatments at 0–10 cm only. The SOC and N concentrations were higher ($p < 0.05$) in the wet-sieved silt-plus-clay fractions and mega-aggregates than macro- and micro-aggregates in the PP and NT at Condobolin, and SR at Merredin, but were similar across aggregates in the CT and RT at Condobolin and SB at Merredin at 0–10 cm depth. Further, at Hermitage, SOC and N concentrations were similar among the aggregate-sizes across different treatments and depths. The only exception was the NT-SR-90N treatment, where SOC and N concentrations were higher ($p < 0.05$) in the silt-plus-clay fractions or micro-aggregates than in mega- and macro-aggregates, obtained by either dry- or wet-sieving. Total S concentration was in the order of macro- ≥ micro- > mega-aggregates across all the treatments and was higher in the PP at Condobolin (0–10 cm depth), and in the SR at Merredin (all soil depths) than the other corresponding treatments. Further, at Merredin, both SR and SB had higher P concentration in macro- and micro- than mega-aggregates. Across all the practices, SOC and N concentrations were higher in the dry- and wet-sieved silt-plus-clay fractions or micro- than mega- and macro-aggregates in both Luvisols, with no differences in the Vertisol. In summary, although the PP, NT, and SR (compared with other corresponding treatments at each site) had minimal impact on total SOC and nutrient stocks in bulk soils, these practices increased aggregate stability in

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https://doi.org/10.1016/j.still.2017.12.019
Received 1 June 2017; Received in revised form 16 December 2017; Accepted 20 December 2017

some systems (*i.e.* Condobolin), and SOC and nutrient concentrations in the silt-plus-clay fractions or micro-aggregates in both Luvisols. These findings suggest that reducing soil disturbance and enhancing crop residue input in farming systems are important for SOC and nutrient storage, particularly in finer aggregate fractions.

1. Introduction

Soil structure is not only a key indicator of soil quality but can also impact on agricultural sustainability due to its relation with many soil properties and processes (Lam et al., 2013; Devine et al., 2014). Further, soil structure can be adversely or favourably impacted by different land management practices, with implications for soil functionality (Hoyle and Murphy, 2006; Dalal et al., 2011; Devine et al., 2014; Somasundaram et al., 2017). A well-structured soil rich in soil organic matter (SOM) may support constant nutrient supply and plant growth, relative to a poorly-structured soil low in SOM (Bronick and Lal, 2005; Bimüller et al., 2016). Moreover, conventional tillage breaks down large aggregates into finer aggregates, and therefore, decreases soil aggregate stability and soil organic carbon (SOC) and nutrient stocks *via* enhancing decomposition of aggregate-protected SOM (Six et al., 2000; Dalal et al., 2011; Zhang et al., 2013), although available nutrients may be temporarily enhanced (Sarker et al., 2018a,b). Therefore, it is important to identify land management practices which have the potential to generate favourable soil conditions, such as high aggregate stability and SOC and nutrient storage, to improve sustainability of agriculture (Li et al., 2007; Devine et al., 2014; Somasundaram et al., 2017). In farming systems, perennial pasture (PP), inclusion of pastures in crop rotations, reduced tillage (RT) or no-till (NT) with stubble retention (SR), and nitrogen (N) fertilisation are some of the improved land use and management practices, which have been recommended to maintain or increase SOM and associated nutrients (Bhupinderpal-Singh et al., 2004; Luo et al., 2010; Dalal et al., 2011; Hoyle et al., 2013; Kopittke et al., 2016).

According to the conventional model of aggregate formation (Tisdall and Oades, 1982), plant- and microbial-derived organic materials bind soil mineral particles to form aggregates. As soil aggregates of different sizes are formed, SOM can be present in both inter-aggregate and intra-aggregate spaces in different forms and amounts with different accessibility to microorganisms depending on aggregate-size classes and management practices (Six et al., 1999; Six et al., 2002; von Lützow et al., 2007). Over the last two decades, several researchers have examined responses of soil aggregate size distribution to management practices and reported a direct linkage between tillage, soil aggregation and the loss of labile forms of SOM from different aggregate-size classes (Jastrow et al., 1996; Six et al., 2000; Jiang et al., 2011; Devine et al., 2014). However, improved land management practices (such as NT, PP or SR) may enhance soil structural stability, by decreasing macro-aggregate turnover, increasing aggregate stability and organic C input, and thus preserving SOC and nutrients in soil structural units, *e.g.* within macro- and micro-aggregates (Six et al., 1998, 2000; Devine et al., 2014; Rabbi et al., 2014). Previous research showed that N fertilisation increased crop yields, straw residue and root biomass input into soil systems, eventually causing an increase in SOC content and soil aggregation (Riley, 2007; Dalal et al., 2011; Tian et al., 2015b).

Soil properties such as soil texture and clay mineralogy can also have a direct correlation with aggregate stability (Denef and Six, 2005; Norton et al., 2006; Ruiz-Vera and Wu, 2006) and SOC stabilisation (Feng et al., 2013; Cowie et al., 2013; Curtin et al., 2016). Clay acts as a cementing agent by interacting with cations and organic molecules in soil (Emerson, 1977; Saidy et al., 2013; Fink et al., 2016) and therefore, can contribute to the formation of aggregates and improved soil structural stability (Boix-Fayos et al., 2001; Denef and Six, 2005). Many researchers have found a linear or exponential relationship between silt-plus-clay content and SOC associated with these particles (Six et al., 2002; Khandakar et al., 2012). For example, clay-rich soils provide larger specific surface areas and numerous reactive sites where SOM can be stabilised *via* ligand exchange and polyvalent cation bridging (von Lützow et al., 2007; Ding et al., 2014). Furthermore, clay mineralogy also plays a significant role in aggregate formation and SOC stabilisation (Reichert and Norton, 1994; Denef and Six, 2005). For example, soils dominated by 2:1 type clay may have greater aggregate stability and SOC stabilisation capacity than soils dominated by 1:1 type clay (Six et al., 2002; Feng et al., 2013).

In Australia, SOC levels were found to be declining in the croplands (Sanderman et al., 2010) and research suggests there is potential to halt or reverse this decline through changing to improved land management practices, such as RT or NT with SR, and mixed crop–pasture rotations (Chan et al., 2003; Cowie et al., 2013; Rabbi et al., 2014; Young et al., 2016). Luo et al. (2010) reported in their review that in Australian cropping systems, the introduction of a perennial grass phase had the potential to cause a relative increase in soil C by 18% compared with cropland under conservation farming practices. Similarly, Chan et al. (2011) reported a significant positive impact of NT and also SR on SOC stocks compared with conventional tillage (CT) and stubble burnt (SB) in a Kandosol after 24 years. Further, Dalal et al. (2011) reported a significantly higher SOC in NT-SR with N fertilisation (*i.e.* 90 kg/ha) than in other treatments such as CT-SR/SB with or without N fertilisation. Although stubble burning reduces stubble load, and weed and disease infestation, this practice could adversely impact SOC and nutrient stocks (Chan and Heenan, 2005; Heenan et al., 2004). However, studies have also reported no change in SOC stocks (Hoyle and Murphy, 2006) or small increase in total N stocks (Dalal et al., 2011) by some of the improved long-term management practices (i.e. NT-SR with or without N fertilisation) in different soils after 16 or 42 years.

There is a recent consensual paradigm that physicochemical protection of SOM offered by soil aggregation and clay minerals is crucial for building and maintaining soil C and nutrient stocks in agro-ecosystems (Six et al., 2002; von Lützow et al., 2007; Lehmann and Kleber, 2015). For example, SOM may be highly stabilised in micro-aggregates (0.25–0.053 mm) and silt-plus-clay fractions (< 0.053 mm), due to the dominance of finer clay particles and their high specific surface areas, which may facilitate long residence time of SOM relative to mega- (> 2 mm) and macro-aggregate (2–0.25 mm) (Six et al., 2002; Feng et al., 2013; O'Brien and Jastrow, 2013).

Currently, we have a general understanding on SOC and total N concentrations in aggregates separated by different physical fractionation techniques (Six et al., 2000; Devine et al., 2014; Rabbi et al., 2014). However, little is known about total S and P concentrations in different aggregate-size classes (Yang et al., 2007; Wei et al., 2013). Further, to our knowledge, few studies have reported the impact of long-term agricultural management practices on SOC, and total N, S and P concentrations in each of the aggregate-size classes. To enhance this understanding, soil samples were collected from three long-term (16–46 years) farming system field experiments. The aggregate-size classes were separated by dry- and wet-sieving, and then the concentrations and stocks of SOC and total N, S and P in bulk soil and aggregate-size classes were measured. We hypothesised that:

(i) Improved management practices (PP, NT, SR and N fertilisation) will promote the formation and stabilisation of mega- and macro-aggregates due to lower soil disturbance, and/or greater organic C input into the system. Hence, these treatments will improve soil aggregate stability, and SOC and total N, S and P stocks and concentrations in bulk soils and different aggregate-size classes, in