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Modelling soil organic carbon storage with RothC in irrigated Vertisols under cotton cropping systems in the sub-tropics

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ABSTRACT

The performance of the Rothamsted Carbon Model (RothC) in simulating soil carbon (SOC) storage in cotton based cropping systems under different tillage management practices on an irrigated Vertisol in semi-arid, subtropics was evaluated using data from a long-term (1994–2012) cotton cropping systems experiment near Narrabri in north-western New South Wales, Australia. The experimental treatments were continuous cotton/conventional tillage (CC/CT), continuous cotton/minimum tillage (CC/MT), and cotton-wheat (*Triticum aestivum* L.) rotation/minimum tillage (CW/MT). Soil carbon (C) input was calculated by published functions that relate crop yield to soil C input. Measured values showed a loss in SOC of 34%, 24% and 31% of the initial SOC storages within 19 years (1994–2012) under CC/CT, CC/MT, and CW/MT, respectively. RothC satisfactorily simulated the dynamics of SOC in cotton based cropping systems under minimum tillage (CC/MT and CW/MT), whereas the model performance was poor under intensive conventional tillage (CC/CT). The model RothC overestimated SOC storage in cotton cropping under conventional intensive tillage management system. This over estimation could not be attributed to the overestimation of soil C inputs, or errors in initial quantification of SOC pools for model initialization, or the ratio of incoming decomposable plant materials to resistant plant materials. Among other different factors affecting SOC dynamics and its modelling under intensive tillage in tropics and sub-tropics, we conclude that factors for tillage and soil erosion might be needed when modelling SOC dynamics using RothC under intensive tillage management system in the tropics and the sub-tropics.

1. Introduction

Cotton is one of the most important commercial crops in the world, accounting for about 2.5% of the world arable land area, and comprising 33–36% of the world fibre consumption (FAO and ICAC, 2013). Cotton is widely grown in the warm-humid to sub-humid tropics and sub-tropics with different management practices on a range of soil types from clay to loam across the world (Franzluebbers et al., 2012; Fultz et al., 2013; Hulugalle et al., 2013; Kamoni et al., 2007; Kintché et al., 2010; Sharma et al., 2011). Cotton is a low-residue returning, but a high soil disturbance crop, and conventionally grown as monoculture due to its economic benefits (Causarano et al., 2006; Fultz et al., 2013). The cotton growing soils are relatively low in soil organic carbon (SOC) due partly to prevailing hot and humid climate conditions and soil mineralogy in the cotton growing regions, but also intensive cultivation, soil erosion, long bare fallow, insufficient return of crop residues under continuous cotton monoculture (Causarano et al., 2006; Hulugalle and Scott, 2008). Conventional tillage and clean cultivation associated with traditional cotton production involve multiple intensive disking, chisel plowing, deep cultivation, harrowing and bed preparation (Reddy et al., 2006). Intensive tillage stimulates microbial breakdown of SOC by disrupting soil aggregates and exposing protected soil organic matter to microbes

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(Teixeira et al., 2013). Tillage also incorporates and mixes residues, improves aeration, which can lead to additional losses of carbon (C) by maximizing soil-residue contact with the soil microbes (Curaqueo et al., 2010; Jacinthe and Lal, 2005). The potential loss of SOC due to tillage is lager in the tropics and subtropics compared to temperate regions (Ogle et al., 2005). Soil erosion associated with intensive cultivation in the cotton production systems also enhances loss of SOC (Gaiser et al., 2008; Franzluebbers et al., 2012). Adoption of conservation tillage technology with limited soil disturbances, diverse crop rotations with high-residue producing crops such as corn and other cereals, cover cropping, sufficient return of crop residues, application of optimum fertilizer, manure and irrigation etc. are keys to restore SOC under cotton cropping systems (Causarano et al., 2006; Franzluebbers et al., 2012; Hulugalle and Scott, 2008).

A review of 20 studies by Causarano et al. (2006) from the cotton belt of the south-eastern USA, reported an increase of SOC by 0.48 ± 0.56 Mg C ha^{-1} yr^{-1} under no tilled cotton cropping compared with conventional tilled cotton. Across a range of soil types from sandy loam to silt loam soils in the sub-tropical cotton belt of the southern USA, Franzluebbers et al. (2012) predicted a potential SOC sequestration by 0.12 ± 0.06 Mg C ha^{-1} yr^{-1} under various no till conservation agricultural managements in the 0–0.20 m soil depth, but a loss of SOC by 0.31 ± 0.19 Mg C ha^{-1} yr^{-1} under conventionally tilled cotton. From a study in the semi-arid sub-tropical Australia on clay soils (Vertisols), Hulugalle et al. (2005) found a 23% higher SOC (1.03 g C kg^{-1}) in irrigated cotton monoculture under reduced tillage compared to conventional tillage (SOC 0.84 g C kg^{-1}) in the 0–0.15 m soil depth. From the world oldest continuous cotton experiment, AL, USA (ca. 1896), Mitchell and Entry (1998) demonstrated that addition of rotation crops (corn along with small grains and legumes) and inclusion of a winter cover crop in the conventional tilled continuous cotton (SOC 4.2 g C kg^{-1}) resulted into 2.9 and 2.3 times higher SOC (12.1 and 9.5 g C kg^{-1}), respectively in the top 0.20 m soil layer on a sandy loam soil after an average of 95 years cropping. The positive effects of crop rotation and cover crop on SOC increase when different reduced tillage systems are combined together. For example, in the Alabama experiment, introduction of conservation tillage into crop rotations and cover cropping of the cotton production systems resulted into an average increase of SOC by 39% within 42 months (Siri-Prieto et al., 2002). Combined positive effects of minimum tillage, crop rotation, cover crop, optimum use of fertilizer and manure have been widely reported under both rainfed and irrigated cotton based cropping systems (Causarano et al., 2006; Fultz et al., 2013; Reddy et al., 2006; Rochester, 2011; Sainju et al., 2007; Sharma et al., 2011). However, benefits of crop rotation, cover cropping and conservation tillage in C sequestration has been reported to be greater under irrigated condition than in dryland cotton (Sainju et al., 2007). As dynamics of SOC under cotton based cropping systems varies depending on the soil types, climate and associated management practices (tillage, crop rotation, irrigation, fertilization etc.) (Franzluebbers et al., 2012; Sainju et al., 2007), more research is needed to better understand the underlying process relating to SOC dynamics, and characterize potential SOC sequestration in cotton based cropping systems especially with regard to the diversity of soil types, climate and management practices.

The studies of SOC dynamics and how it is influenced by different environmental and management-induced changes are costly and time consuming, usually allowing the study of only a few variables and their interactions at one time (Rabbi et al., 2013). The SOC models are an alternative to investigate SOC dynamics and to explore the possibilities for modification of SOC through different management practices (Falloon and Smith, 2009; Smith and Smith, 2007). Simulation models encompass our best knowledge to predict variation in SOC dynamics associated with a specific environmental and management modification (Smith et al., 1997a). Among the many SOC models published, the Rothamsted Carbon Model (RothC) (Coleman and Jenkinson, 1996) has a simplier structure than other models, and the advantage of using the model is that it requires few input parameters which are easily obtainable. Again, RothC is one of the best performing model across the world (Smith et al., 1997b). However, the use of any model under specific environmental and management condition requires a validation procedure with local observed SOC contents (Smith et al., 1997b). Although the model RothC has been thoroughly tested in different climatic regions using long-term experiments (Ludwig et al., 2007; Smith et al., 1997b; Studdert et al., 2011), validation of the model is limited in tropics and subtropics (Diels et al., 2004; Kamoni et al., 2007; Shirato et al., 2005; Skjemstad et al., 2004) particularly in cotton-based cropping system on irrigated Vertisols under different tillage management systems, due to the scarcity of long-term data sets (Kintché et al., 2010).

The aims of our study was to test the RothC model in cotton-based cropping systems on irrigated Vertisols under conventional and minimum tillage management practices using long-term field experimental data sets from the semi-arid sub-tropics.

2. Materials and methods

2.1. Experimental site

The field experiment is located at the Australian Cotton Research Institute, near Narrabri, in north-western New South Wales (NSW), Australia (149°47′ E, 30°13′ S). The experimental site has a subtropical, semi-arid climate. The soil at the experimental site is a uniform alkaline, self-mulching, deep grey clay, classified as a Vertisol (Isbell, 2002), or fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010). The soil in the experimental site and across the entire research centre is highly uniform, and soil variability across the experimental site is minimal (Ward et al., 1999). Mean particle size distribution in the 0–0.3 m depth was: 53 g 100 g^{-1} clay, 21 g 100 g^{-1} silt and 26 g 100 g^{-1} sand; $CaCO_3$ concentration was 0.5 g 100 g^{-1}. The individual treatment plots were 190–200 m long and 32–36 rows wide. The rows (beds) were spaced at 1 m intervals.

2.2. Treatments and crop management

The experiment, which have been implemented since 1985 with a randomized complete block design with four replicates, consisted of three crop rotation/tillage combinations viz. (1) continuous cotton/conventional tillage (CC/CT): summer cotton-winter fallow sequence, where cotton was sown with intensive conventional tillage *viz.* disc-ploughing (offset disc-40 plate, Ennor Engineering, Deniliquin, NSW, Australia) and incorporation of cotton stalks to 0.2 m, chisel ploughing (Scaribar-12 tyne, Horwood Bagshaw, Adelaide, Australia) to 0.3 m followed by bed construction in each year, (2) continuous cotton/minimum tillage (CC/MT): summer cotton-winter fallow sequence, where cotton was sown with minimum tillage *viz.* slashing cotton plant after harvest with a slasher (4 m, John Shearer Ltd., Kilkenny, Australia), followed by root cutting and bed renovation with disc-hiller (Go-Devils 8 m, Gessner Industries, Toowoomba, Queensland, Australia) i.e. cotton was sown each year on permanent beds with limited soil disturbance, and (3) cotton-wheat/minimum tillage (CW/MT): summer cotton-winter wheat-summer fallow-winter fallow sequence, where cotton and wheat were sown with minimum tillage. All crop residues were retained in situ under all the treatments. Wheat stubble in the CW/MT system was incorporated into beds until 1999; thereafter standing wheat stubble was retained as mulch during the fallow period of 9–10