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Irrigation induced surface carbon flow in a Vertisol under furrow irrigated cotton cropping systems

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ABSTRACT

Pathways of sequestered carbon loss from cotton (*Gossypium hirsutum* L.) farming systems include the carbon transported off-site in runoff and erosion. There is a lack of field studies that quantify the carbon gains and losses in hydrological pathways in cotton and other irrigated row cropping systems A three-year field investigation was overlaid on a long-term experiment near Narrabri, New South Wales, Australia with the objective to evaluate the effect of tillage practices and crop rotations on carbon loads in irrigation and runoff waters, and their impact on soil carbon balance in an intensive cotton production system. The treatments included maximum or minimum tillage sown with cotton monoculture, cotton-wheat (*Triticum aestivum* L.) or cotton-maize (*Zea mays* L.) rotations. Maximum tillage consisted of slashing of cotton plants after harvest, followed by disc-ploughing to incorporate the cotton stalks to 0.2 m, followed by chisel ploughing to 0.3 m, then 1 m bed construction. For minimum tillage, slashing was followed by root cutting, then incorporation of cotton stalks into beds (0.1 m) and followed by bed renovation with a disc-hiller. The minimum-tilled cotton-wheat rotation included similar tillage operations after cotton, however maize or cotton was planted into standing wheat stubble with zero tillage. Irrigation volume, sediment, and total and dissolved organic carbon gains and losses during irrigation were monitored during the 2014–15, 2015–16 and 2016–17 cotton seasons. Runoff from maximum-tilled and minimum-tilled cotton monoculture systems averaged 32% and 40%, respectively, of applied irrigation. Irrigation-induced total organic carbon (TOC) losses in runoff from the cotton field were influenced by tillage during 2015–16 and ranged from 24 to 72 kg ha^{-1} year^{-1} across three years. Net TOC enrichment of cotton field soils by irrigation water ranged from 30 to 265 kg TOC ha^{-1}. Overall, the average seasonal net carbon gains in irrigation water were equivalent to mitigating 4.7 to 24% of long term annual soil organic carbon (SOC) decline rate in the same experiment. Storm events intensified the movement of carbon and soil from bed to furrows. These sediments were prone to further erosion during subsequent irrigations. Minimum tillage can minimise carbon losses in runoff when combined with a crop sequence such as cotton-wheat-maize. Consequently, research on soil carbon sequestration in irrigated systems must account for carbon flow during irrigation because it is a significant factor in the carbon balance. Long term monitoring over several years is needed to quantify storm-induced carbon losses in semi-arid limited rainfall environments.

1. Introduction

Cotton (*Gossypium hirsutum* L.) production in Australia is concentrated in the eastern states of New South Wales and Queensland and has an annual gross value of $2 billion (AUD) (Roth, 2014). Cotton farm size in Australia ranges from less than 50 ha to greater than 2000 ha with an average farm size of 495 ha (Cotton Australia, 2016) and occurs mainly on Vertisols (Hulugalle and Scott, 2008). Approximately 92% of irrigated cotton production takes place under conventional and 2.5% under bank-less furrow irrigation (Roth Rural, 2015). Conventional furrow irrigation consists of a defined head-ditch with water siphoned to furrows, whereas under bank-less furrow irrigation water flows directly from the main channel to the field, and from field to field.

The implementation of intensive agricultural practices across the world such as mechanised cotton farming has led to rapid declines in soil organic carbon (SOC) reserves (Kirschbaum et al., 2008).

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Conservation farming practices implemented with the assumption that they may reverse these losses, in many instances, have proven to be ineffective (Powlson et al., 2011). This may be related to the fact that pathways of carbon loss have not been well elucidated for sub-humid to arid climatic regions (Stockmann et al., 2013). Most authors have assumed that the major pathway of soil carbon loss is microbial respiration (Huon et al., 2013; Stockmann et al., 2013). While, this has been largely overlooked in the past, part of this decline is thought to be due to an unaccounted carbon loss through soil erosion (Chappell et al., 2015; Hulugalle et al., 2013; Johnson et al., 2014) and deposition at other sites, or a carbon loss mechanism associated after the erosion event (Lal, 2003). Deep drainage leaching losses of dissolved organic carbon (DOC) may also be another important pathway of carbon loss from agricultural systems (Kindler et al., 2011). The global literature on soil erosion suggests an annual discharge rate of 15–20 billion tonnes of sediments into the ocean (Lal, 2003). These sediments could carry a significant amount of soil carbon (Quinton et al., 2010). On-farm studies on nutrient flux have mostly focussed on nutrient and sediment load with only a few monitoring seasonal or annual organic carbon flux (King et al., 2009; Lentz and Lehrsch, 2014; Nachimuthu et al., 2016; Ruark et al., 2010).

Soil carbon research in various farming systems in Australia was comprehensively reviewed by Baldock et al. (2013). However, none of the studies cited by these authors addressed carbon losses through terrestrial non-gaseous pathways such as soil erosion and runoff or carbon gains from irrigation and flood water. Although some researchers have reported the impact of soil erosion on SOC pools and their spatial distribution at different stages of erosion (Lal, 2005; Shukla and Lal, 2005)) there is a general paucity of information on the terrestrial hydrological pathways of SOC loss or gain under Australian conditions. Methodologies for carbon stock accounting in Australian farming systems have been proposed (*e.g.* Soil carbon research program-SCaRP) (Baldock et al., 2013), but soil carbon losses and gains through terrestrial hydrological pathways were excluded (Chappell et al., 2015). The absence of such empirical data is one of the reasons for an omission. Many Australian soil erosion studies have not reported particulate or dissolved carbon losses associated with soil erosion, although a few reported some carbon fractions under pasture systems (Fleming and Cox, 2001; Ghadiri et al., 2011; Nachimuthu and Hulugalle, 2016).

There is a paucity of empirical studies on the links between crop management practices and the carbon flux in hydrological pathways in cotton and other irrigated row cropping systems. This study evaluated the effect of tillage practices and crop rotations on sediment and carbon loads in irrigation and runoff waters, and their impact on soil carbon balance in an intensive cotton production system. We hypothesised that carbon losses in runoff leads to sequestered carbon losses in cotton farming systems of Australia. Our study is the first of its kind for the Australian cotton industry and was aimed at addressing the above-mentioned knowledge gap on surface carbon flow in terrestrial hydrological pathways in cotton farming systems.

2. Materials and methods

2.1. Site description

The experimental site was located at the Australian Cotton Research Institute, near Narrabri (149°47′E, 30°13′S), north-western New South Wales, Australia. The experimental site has a semi-arid climate. The hottest month is January (mean daily maxima and minima of 34 and 20 °C, respectively) and July is the coolest (mean daily maxima and minima of 18 and 4 °C, respectively). Mean annual rainfall is 568 mm with more than 50% of rainfall occurring during the cotton growing season (October-March). The soil is a deep uniform grey clay and is classified as a fine, thermic, smectitic, Typic Haplustert (Soil Survey Staff, 2010). The soil at 0-0.3 m depth is alkaline (pH in 0.01 M $CaCl_2$ is 7.4), non-saline (electrical conductivity ($EC_{1:5}$) is 0.11 dS m^{-1}), has an ESP of 2.2 with exchangeable cation concentrations of 17, 8.8, 1.13 and 0.56 cmol (+) kg^{-1} for calcium, magnesium, potassium and sodium respectively, and particle size distribution of 53 g 100^{-1} g clay (< 2 μm), 21 g 100^{-1} g silt (2–20 μm) and 26 g 100^{-1} g sand (20 μm – 2 mm).

2.2. Experimental treatments

This investigation was overlaid on a long term experiment on tillage practices and cotton rotations; viz. cotton monoculture sown after either maximum or minimum tillage, and a minimum-tilled cotton-wheat rotation (Constable et al., 1992). Maximum tillage consisted of slashing of cotton plants after harvest, followed by disc-ploughing and incorporation of cotton stalks to 0.2 m, chisel ploughing to 0.3 m followed by 1-m spaced bed construction. Minimum tillage also included slashing of cotton plants after harvest, but was followed by root cutting, then incorporation of cotton stalks into beds, and then bed renovation with a disc-hiller. Conventional cotton was sown until 1999, Round-up Ready cotton from 2000 to 2006, and “Bollgard-Roundup Ready Flex” varieties thereafter. The field has a slope of 0.1% from head end to tail end (supplementary data). The experiment was re-designed in 2011 such that all plots were split by either sowing a maize (*Zea mays* L.) crop during the summer following the previous year’s cotton (with respect to the cotton-wheat, this involved sowing maize immediately after wheat but before the next year cotton crop) or retaining the historical cropping system as a control. The current six treatments, thus, were: (1) maximum tillage cotton monoculture (MXT-CC), (2) maximum tillage cotton maize (MXT-MC), (3) minimum tillage cotton monoculture (MNT-CC), (4) minimum tillage cotton maize (MNT-MC), (5) minimum tillage cotton-wheat (MNW-C) and (6) minimum tillage cotton-wheat-maize (MNW-MC) rotations (Table 1). The experimental design was a split-plot design where the historical tillage/rotation system combinations were designated as main plot treatments and +/- maize as subplots, replicated four times. In summary, there were three main plots and two sub plots per main plot in each replication. The field layout, dimension and number of rows within each plot are presented in Figure S1 (supplementary data).

2.3. Crop management

2.3.1. Cotton

Cotton was planted (seed rate @ 18 kg ha^{-1} or 12–15 seeds m^{-2}) in October/November every year. The cotton varieties sown were: Sicot 71 BRF® (2011–2013, 2015), Liberty link® Sicot 70 BL (2014) and Sicot 746 B3F (2016). Cotton received fertiliser N as surface applied urea (180 kg N ha^{-1} after sowing and 80 kg N ha^{-1} during January, if required) in all years except during 2015 when it was drilled into the beds (0.1 m deep) before sowing on either side of the planting row. The comparison between years for yield, fertilisation method and nutrient losses were not assessed as it was not the focus of this study. Cotton was irrigated at a rate of 100 mm per irrigation when rainfall and soil water storage could not meet evaporative demand (Table 2). The water was delivered through a furrow irrigation system that had beds spaced at one metre intervals (supplementary data, Photo 1). This layout is typical of irrigated row crop systems in New South Wales and Southern Queensland. Weeds were controlled through a combination of hand-hoeing, inter-row cultivation and herbicides. Defoliation occurred between late March and early April every year when at least 60% of bolls had opened and picking during April or May with a mechanical four-row cotton picker. The cotton plants were then slashed to a height of 0.1 m, after which a tractor-driven root cutter cut the root system ~50 mm below the surface of the bed.

2.3.2. Maize

Maize (*cv. Pioneer 31G66 during 2011, Var P1070 in 2013 and Var*