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Review

A review of the soil science research legacy of the triumvirate of cotton CRC

Stephen R. Cattle[A,B] *and Damien J. Field*[A]

[A]Department of Environmental Sciences, Faculty of Agriculture and Environment, The University of Sydney, NSW 2006, Australia.
[B]Corresponding author. Email: stephen.cattle@sydney.edu.au

Abstract. For nearly two decades (1994–2012) a series of three consecutive Cooperative Research Centres (CRC) dealing with cotton production provided the impetus and financial support for a substantial body of soil science research in eastern and northern Australia. Focusing on the most commonly utilised soil for irrigated crop production, the Vertosol, CRC-affiliated soil researchers undertook detailed soil inventories of cotton-growing valleys in New South Wales, and tackled a range of applied soil research questions that faced the entire Australian cotton industry. Across the broad categories of soil mapping and characterisation, soil physical condition, salinity and sodicity, soil chemical fertility, and soil carbon and biota, some 120 CRC-affiliated research papers were published in peer-reviewed journals during the years of the CRC. Findings from this body of research were fed back to the industry through conferences, extension workshops and materials, and to a lesser extent, the peer-reviewed publications. In certain cases, underpinning basic research was carried out concurrently with the more applied research, meaning that the cotton CRC were effectively supporting advances in the discipline of soil science, as well as in sustainable cotton production. A feature of the soil research portfolio over the span of the three cotton CRC was that priorities shifted according to the interplay of three factors; the natural maturation of research topics and the concomitant evolution of cotton farming systems, the rising importance of environmental implications of agricultural land use, and the emergence of carbon as a national research priority. Furthermore, the commitment of the CRC to education resulted in the involvement of undergraduate and postgraduate university students in all aspects of the soil research effort. A legacy of the triumvirate of cotton CRC is a wide-ranging body of both applied and basic knowledge regarding the physical, chemical and biological attributes of Australian Vertosols used for irrigated agriculture.

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Introduction

Between the years of 2005 and 2012, the Cotton Catchment Communities Cooperative Research Centre (Cotton CRC) was a prominent vehicle for research into various aspects of cotton-growing soils, building on the legacy of soil research conducted under the auspices of the CRC for Sustainable Cotton Production (CRC-SCP; 1994–99) and the Australian Cotton CRC (AC-CRC; 1999–2005). The soil type upon which the vast bulk of this research was conducted is the Vertosol. Prior to 1994, the Vertosol (Black Earths; Grey, Brown and Red Clays; Wiesenboden) had been subjected to considerable research in various locations around Australia by university, CSIRO and state government department researchers. Many important papers and reports detailing the characteristics and behaviour of this distinctive global soil type were published from Australian research in the period 1950–85. As examples, the formation and landscapes of Vertosols had been investigated by Hallsworth *et al*. (1955) and Beckmann *et al*. (1973), while the drainage and other hydraulic features of Vertosols had been investigated by Talsma and van der Lelij (1976) and McIntyre *et al*. (1982). In 1981, a symposium on the properties and utilisation of cracking clay soils was held at the University of New England, Armidale, New South Wales (NSW) featuring an array of high profile Australian soil scientists and giving rise to an important Proceedings volume of the same name (McGarity *et al*. 1984). Given the large expanse of Vertosols across Australia (~12% of the country; Isbell *et al*. 1997) and the well recognised agronomic potential of this soil type, it was not surprising that such research effort had been dedicated to it.

By the late 1980s, a substantial body of literature dealing with Vertosols as an integral part of irrigated cotton production systems in eastern Australia, had started to emerge. Driven primarily by researchers in the NSW Department of Agriculture and the CSIRO, irrigation strategies (Constable and Hearn 1981), trafficking and tillage effects (McGarry 1987; Daniells 1989), macronutrient uptake (Hearn 1981, 1986) and micronutrient uptake (Constable *et al*. 1988), in and for cotton-growing Vertosols, had been investigated. Many of the findings of these publications became incorporated into the first two editions of SOILpak for cotton growers (Daniells and Larsen 1990, 1991), the main soil science extension vehicle for the cotton industry at the time. In the early 1990s the heavy emphasis on soil structural condition (Hodgson *et al*. 1990; McGarry 1990; Hulme *et al*. 1991; McKenzie *et al*. 1991;

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Little *et al*. 1992) and crop nutrition (Rochester *et al*. 1991, 1993; Constable *et al*. 1992) in cotton-growing Vertosols continued, such that when the inaugural World Cotton Conference was held in Brisbane in early 1994, these two topics constituted the most prominent soil-related sessions (Constable and Forrester 1995).

With the advent of the CRC-SCP in that same year, 1994, there emerged an opportunity for a program of coordinated, multi-organisation research on the characteristics, behaviour and management of soils, particularly Vertosols, used for cotton production. In many ways, the World Cotton Conference set the agenda for the first cotton CRC, as the various sessions demonstrated the range of research issues posed by irrigated cotton production on Vertosols in eastern Australia.

The purpose of this review is to reflect on the contribution of the three cotton CRC to soil research in Australia, with a particular emphasis on the outputs of the Cotton CRC and on the science of Vertosols. Due to the inherently collaborative nature of the CRC, and the strong alliance that the CRC had with the Cotton Research and Development Corporation (CRDC) in funding research, it is sometimes difficult to separate the relative contributions of these organisations to research outputs, so we have attempted to include all relevant research outputs (mainly peer-reviewed journal papers) that acknowledge the cotton CRC or CRDC as a funding body. Some of the cited research was not funded by the cotton CRC or CRDC, but we have included it because of its relevance to the cotton industry and/or the science of Vertosols, and because in most cases the researchers concerned were involved with the CRC/CRDC on other projects. We have also attempted to categorise the soil research outputs of the cotton CRC into five general categories, but not surprisingly there are many papers that could easily fit into more than one category. Only those outputs that specifically acknowledge the cotton CRC are included in the yearly counts for each category. Finally, we have attempted to review the strong role that the cotton CRC played in soil science extension and education for the cotton industry over 18 years.

Soil mapping and characterisation

Mapping and characterisation of soils in cotton-growing valleys was a strong focus of all three cotton CRC, leading not only to up-to-date maps of soil attributes for many areas, but also to conceptual advances in soil survey methodology and data capture techniques. During the years of the CRC-SCP, as various soil survey programs were getting underway in different cotton-growing valleys, most of the publications in this topic area concerned the use of new and evolving statistical (McBratney and Odeh 1997) and spatial prediction techniques (Odeh *et al*. 1995, 1998) for soil survey. In some cases (e.g. Odeh *et al*. 1998), pre-existing soil datasets from cotton-growing areas, such as the Edgeroi dataset of McGarry *et al*. (1989) were used to illustrate the new techniques being developed. The use of applied soil survey at the cotton-field scale was also discussed in the early years of the CRC-SCP, through the emergence of site-specific management as a potential innovative technology for the Australian cotton industry (McBratney and Whelan 1995; Stewart *et al*. 2005).

By the year 2000, results of the soil mapping programs initiated in the preceding 6 years began to appear (Fig. 1), with clay content (Odeh and McBratney 2000), salinity

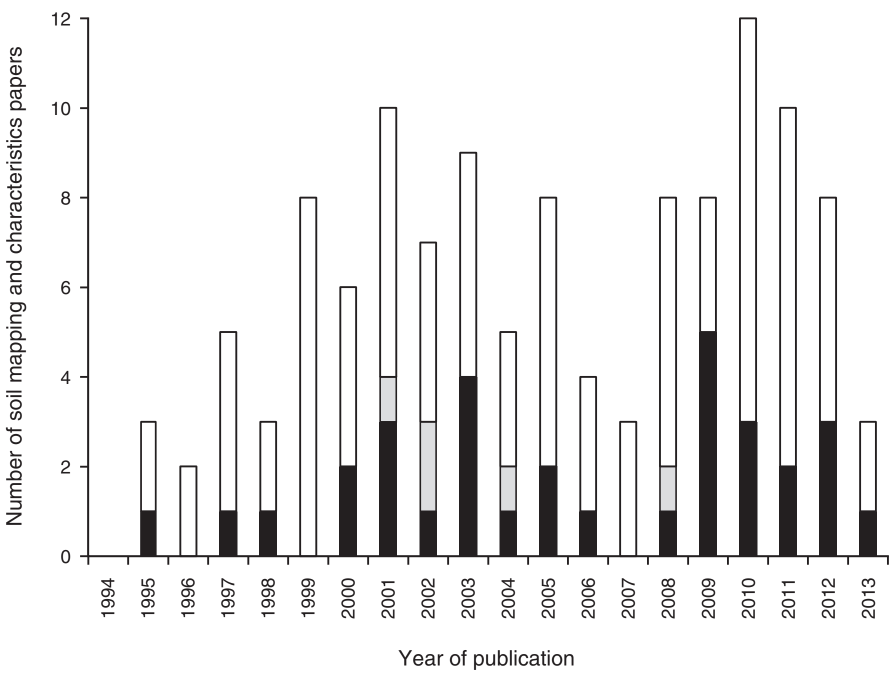

Fig. 1. The number of Cooperative Research Centre (CRC)-affiliated, peer-reviewed journal papers dealing primarily (black column) and secondarily (grey column) with soil mapping and characteristics published in each year of the CRC, and the total number of CRC-affiliated, soil-related papers published in each year (height of column).

(Triantafilis *et al*. 2004*b*), deep drainage (Triantafilis *et al*. 2003*a*, 2004*a*), pH (Singh *et al*. 2003) and carbon (C) content (Knowles and Singh 2003) being among the soil attributes mapped at various locations. These attribute maps were published at field, district and regional scales, across the Namoi, Gwydir, Macquarie and Macintyre valleys. In many cases, the maps produced in these papers, while useful for cotton growers and land managers in those areas, were perhaps more remarkable for the sampling, measurement and statistical techniques that were being developed to produce them. The development of more refined spatial prediction techniques for sparse soil datasets (e.g. Odeh *et al*. 2003), the use of terrain and/or remotely sensed data to assist in the spatial prediction of topsoil attributes (e.g. Odeh and McBratney 2000), using electromagnetic (EM) induction surveys to interpolate clay content across fields (e.g. Triantafilis *et al*. 2001*a*; Triantafilis and Lesch 2005), the development of on-the-go sensing equipment (Triantafilis *et al*. 2002), and the development of fuzzy, or numerical, classification schemes to describe the distribution of soil horizons (Triantafilis *et al*. 2001*d*) and land-use suitabilities (Triantafilis *et al*. 2001*c*), were all conducted during this mapping program. Some of these cotton-growing valley soil datasets were also used to demonstrate advances in pedometric techniques for soil survey (McBratney *et al*. 2000) and to develop soil inference systems using pedotransfer functions (McBratney *et al*. 2002). From the standpoint of the soil science discipline, it is this broad group of methodological journal papers that have had the greatest impact across all of the cotton CRC outputs; eight of these papers have been cited more than 50 times in the scientific literature, and three of them more than 130 times.

In 2004, a database of soil data collected from surveys in the Macintyre, Gwydir, upper Namoi, lower Namoi and Lachlan valleys, was released on CD-ROM (Australian Cotton CRC 2004; Odeh *et al*. 2004). This database contained measurements from ~5000 soil samples, and included estimates of topsoil organic carbon (OC) and phosphorus (P) content, clay content, pH, electrical conductivity, exchangeable cation concentrations and exchangeable sodium percentages (ESP). A limited number of attribute maps were included on the CD-ROM as an accompanying soil information system. In 2006, a geographical information system (GIS) containing soil survey data from the Hillston cotton district of the lower Lachlan valley was released on CD-ROM (University of Sydney 2006), and distributed to growers in that region. More recently, much of this baseline soil survey data has been included in the Soil and Landscape Grid of Australia, being assembled by the Terrestrial Ecosystem Research Network (TERN). This piece of national information infrastructure should ensure greater accessibility and utilisation of the soil survey data collected under the auspices of the CRC.

Building on the legacy of the CRC-SCP and AC-CRC, mapping projects of the Cotton CRC focussed on deep drainage and salinisation risk (e.g. Vervoort and Annen 2006; Triantafilis and Buchanan 2009, 2010; Woodforth *et al*. 2012), the use of different covariates and instruments for predicting soil attributes (e.g. Viscarra Rossel *et al*. 2008; Triantafilis *et al*. 2009*a*, 2013*a*), and on digital soil mapping techniques (e.g. Nelson and Odeh 2009; Triantafilis *et al*. 2009*a*, 2009*b*, 2013*a*). These projects, and the resultant set of papers (Fig. 1), indicate a continued shifting away from expensive and labour-intensive 'traditional soil surveying' of previous decades, and the embracing of digital age technology (e.g. remote sensing techniques) to 'add value' to previous survey datasets and to help 'fill in the gaps' for areas that had not been visited or sampled in past surveys. The digital mapping of soil C storage in the lower Namoi valley (Minasny *et al*. 2006) using the Edgeroi soil dataset (McGarry *et al*. 1989) and various environmental datasets is a good example of this.

In the case of the mapping work on deep drainage and salinisation risk, slightly different approaches were taken by different researchers to identify the role that palaeochannels might play in deep drainage and salt movement. Vervoort and Annen (2006) analysed EM38 and EM34 data from a Gwydir valley field to identify the location of a less clayey palaeochannel, and then used pedotransfer functions to predict the saturated hydraulic conductivities of those palaeochannel sediments. With apparent electrical conductivity data obtained by a DUALEM-421 device in the same field, Monteiro Santos *et al*. (2011) used inversion algorithms to estimate the shape and connectivity of a palaeochannel. In the Darling River valley, Triantafilis and Buchanan (2009) carried out a broad-scale EM34 survey of the Bourke Irrigation District, and then used fuzzy K-means analysis of the EM data to estimate the spatial distribution of four different types of sediments in the area. They drew various conclusions on the likely role of these different sediment bodies in hydrologic and secondary salinisation processes for the Bourke district.

Using the same Bourke EM34 dataset, plus EM38, radiometric, morphometric and some watertable depth data, Buchanan and Triantafilis (2009) used stepwise multiple linear regression analysis to predict the watertable depth at an interval of 100 m across the entire district. This use of ancillary environmental data to aid in mapping also underpinned the research of Nelson and Odeh (2009), Triantafilis *et al*. (2009*a*) and Triantafilis *et al*. (2013*a*), who digitally mapped soil type across the entire Namoi catchment, cation exchange capacity (CEC) across a Namoi valley cotton field, and soil mapping units across the lower Namoi valley, respectively. While the Nelson and Odeh (2009) paper was focussed more on the methodology of using environmental covariates to map soil classes over large and heterogeneous regions, and the Triantafilis *et al*. (2009*a*, 2013*a*) papers on utilising collected EM induction and radiometric data to predict other attributes, all three papers demonstrate that the future of landscape mapping lies in the utilisation of the ever-increasingly available sets of environmental data (e.g. elevation and terrain attributes, magnetic data, radiometric data, spectral data from air photos and satellite imagery) generated by different organisations and governments.

A further data source that is likely to be increasingly utilised in future soil science research is that of spectral libraries for soil materials, particularly for the visible and near-infrared and mid-infrared parts of the EM spectrum. Viscarra Rossel *et al*. (2008) utilised the legacy soil samples of the mapping program described in Odeh *et al*. (2004) to produce a mid-infrared spectral library for soils (mainly Vertosols) of the northern NSW cotton-growing valleys. It seems likely that such a spectral library will become increasingly utilised as spectral equipment is developed for rapid sensing of soil attributes in the field. Similarly, the use of portable X-ray fluorescence (pXRF) spectrometry to rapidly measure the concentrations of agriculturally important elements in the field appears likely to increase, with McLaren *et al*. (2012) demonstrating the efficacy of a pXRF in determining the elemental composition of 20 Vertosols from northern NSW.

Soil physical condition

Vertosols exhibit quite unique physical behaviour because of the high proportion of shrink-swell clay minerals, mainly smectites, present (Hubble 1984). The non-rigid and fine-grained character of these soils means that much water can be stored upon wetting, hydraulic conductivity is generally very small, and that large shrinkage cracks open up upon drying. These attributes make Vertosols ideal for irrigation, but bring with them several challenges for management, including delayed trafficking after rainfall, a propensity for subsurface compaction (e.g. Sullivan and Montgomery 1998), and a propensity for dispersion where sodium is a dominant exchangeable cation (McKenzie 1998). Prior to the commencement of the CRC-SCP, the issue of subsoil physical condition, and in particular subsurface compaction, had been a very strong focus of soil research for the cotton industry (e.g. McGarry 1987; McKenzie *et al*. 1991; Constable and Forrester 1995). Not surprisingly, during the years of the CRC-SCP and AC-CRC, considerable research effort was directed towards mitigating soil compaction under irrigated farming systems, and investigating the structural stability of Vertosols when subjected to wetting.

Various management strategies for the maintenance and improvement of soil structural condition in irrigated Vertosols were investigated by CRC and CRDC-funded researchers. These strategies included the conversion from intensive tillage practices to minimum or reduced tillage practices (Hulme *et al*. 1996; Hulugalle and Entwistle 1997; Chan and Hulugalle 1999), the planting of rotation crops and the incorporation of plant residues (Hulugalle and Cooper 1994), and the implementation of permanent beds of varying widths (Hulugalle *et al*. 1996, 2002*b*). The main research findings from this body of work can be summarised as: (*i*) the simple conversion from conventional tillage to minimum till practices is insufficient to overcome or repair subsoil compaction; (*ii*) the inclusion of rotation crops into cotton production systems has a generally positive effect on soil physical condition; (*iii*) the incorporation of (green manure) crop residues is of substantially greater benefit to soil physical condition than mulching those residues; and (*iv*) wider, 'permanent' beds with controlled traffic down designated wheel lanes will deliver better soil physical condition over the longer term.

The assessment of soil compaction and structural condition in Vertosols during the CRC-SCP and AC-CRC was carried out using a variety of techniques, including visual assessment (e.g. McKenzie 2001*a*), mean aggregate diameter, soil strength and density measures (e.g. Hulugalle *et al*. 1996, 2001*b*), assessment of paint infiltration (e.g. Hulugalle *et al*. 1997) and image analysis methods (e.g. Koppi *et al*. 1994). Of these, the image analysis method was the most laborious, but it offered the greatest quantitative detail of the structural condition of soil; this method had previously been the domain of soil micromorphologists, but a customised image analysis software, Solicon (Cattle *et al*. 2001), was developed and used by researchers working with the cotton CRC and/or the CRDC to quantify profile and horizon structural form attributes in Vertosols (e.g. McKenzie 2001*b*; McKenzie *et al*. 2001; Roesner 2003; Vervoort *et al*. 2003; Speirs *et al*. 2011). With the recent development of methods for using medical scanners to model 3-dimensional soil structural form (e.g. Marchuk *et al*. 2012), the image analysis techniques developed by CRC researchers during the late 1990s and early 2000s have been largely superseded, but at the time they were forming the vanguard of efforts to quantify soil structural form.

The other soil structure focus of the CRC-SCP and AC-CRC, that of assessing soil structural stability to wetting, was a direct response to the challenge of working with OC-depleted topsoil and/or sodium-rich subsoil in irrigated cotton systems. One of the first outputs in this area of research was the release of an improved and easy-to-use method for estimating the instability of Vertosols to wetting, the so-called ASWAT test (Field *et al*. 1997). This test specifically assesses a Vertosol's propensity to disperse when wetted, and was adopted in the SOILpak for cotton growers the following year (McKenzie 1998). Subsequent research into the disaggregation behaviour of Vertosols (Field and Minasny 1999; Field *et al*. 2004) was more fundamental in nature, but nevertheless demonstrated that the size of microaggregates 'liberated' by wetting and/or energy input was related to other soil physico-chemical properties such as ESP, and was important for estimating the likelihood of surface sealing.

The relationships between soil structural attributes, water storage, hydraulic conductivity and crop water-use efficiency, all crucial considerations for successful irrigated cropping, were documented and analysed for cotton-growing Vertosols by various research groups. Taking a broad view, Vervoort *et al*. (2003) measured and compared the hydraulic and structural properties of Vertosols from the Darling Downs, and the Gwydir, Namoi, Macquarie and Lachlan valleys. They concluded that, across these valleys, soil structural form and consequently hydraulic conductivity, are strongly affected by overburden pressure (i.e. depth in the profile), sodicity and the suite of clay minerals present. At the field scale, Weaver *et al*. (2005) measured deep drainage in a Vertosol subjected to various rotation crop and tillage regimes, and determined that the frequency of irrigation, the application of gypsum and type of rotation crop employed could all have an influence on structural condition and deep drainage rates. Putting soil water storage and drainage losses into an agronomic context, Tennakoon and Milroy (2003) estimated the water-use efficiency of irrigated cotton crops across the major cotton-growing valleys of southern Queensland and northern NSW. Although only soil water contents were used in this modelling work, their findings indicated that irrigation efficiency varied considerably within valleys, suggesting that both irrigation management (Montgomery 2003) and management of soil physical condition at the field scale, were important. Finally, advances in techniques for measuring and predicting various soil hydraulic attributes were also made under the auspices of the AC-CRC (Weaver and Hulugalle 2001; Minasny and Field 2005; Vervoort *et al*. 2006).

As the AC-CRC wound down and the Cotton CRC commenced, research continued on the effects of different soil and crop husbandry practices on soil structure, water storage and hydraulic conductivity in Vertosols (e.g. Tennakoon and Hulugalle 2006; Hulugalle *et al*. 2007, 2010*b*, 2012*a*, 2012*d*; Weaver *et al*. 2013). The results of these studies added further weight to the notion that minimum tillage, the maintenance of permanent beds, rotation crops such as wheat, and stubble retention were generally beneficial for soil structural condition and subsequent cotton crop water-use efficiency. Accompanying these improved structural conditions, however, have been reports of increased drainage of water through irrigated profiles; in their 6-year-long trial of four different irrigated cotton-rotation systems in the Namoi valley, Hulugalle *et al*. (2012*d*) reported that a cotton-wheat rotation resulted in greater soil water storage than continuous cotton, but also in greater drainage during the wheat rotation. Furthermore, the salinity of the leachate (drainage water) measured by Hulugalle *et al*. (2012*d*) was ~6 times greater than the salinity of the irrigation water, suggesting the possibility of salinisation of shallow groundwater resources. A subsequent paper by Weaver *et al*. (2013), dealing with the drainage water quality of several sites in the Namoi valley, re-iterated the potential for salinisation and sodification of groundwater under conditions of improved drainage.

The consideration of deep drainage losses and leachate quality is somewhat emblematic of the soil physical condition research conducted during the lifetime of the Cotton CRC, which had greater emphasis on the environmental implications of soil physical condition than previously. Combined with the production-focussed soil physical condition research, this more environmentally-focussed research lead to somewhat of a surge in soil physical condition papers in the second half of the Cotton CRC (Fig. 2). Significant effort was dedicated to better predicting and assessing surface runoff from (e.g. Silburn and Hunter 2009), and deep drainage under (e.g. Gunawardena *et al*. 2011), irrigated cotton production and the development of methods to estimate these. The surface runoff research carried out by Silburn and Hunter (2009), which built on earlier findings that cotton bed architecture, wheel traffic and surface cover were all crucial determinants of runoff and sediment loss from Vertosols under storm conditions (Silburn and Glanville 2002), focussed on nutrient losses from cotton fields in runoff and sediment. They estimated that total annual losses of (fertiliser-) applied nitrogen (N) and P in runoff water could approach 15 and 10%, respectively, where surface cover was lacking and subsurface compaction impeded infiltration (Silburn and Hunter 2009). To directly measure the amount of water draining through Vertosols during an irrigation season, Gunawardena *et al*. (2011) set up lysimeters at a depth of 1.5 m in irrigated cotton fields at nine locations in southern Queensland and northern NSW. They found that deep drainage varied considerably both spatially and temporally, but that up to a quarter of applied irrigation water could be lost to deep drainage in some circumstances (Gunawardena *et al*. 2011), and that draining water was considerably more saline than the applied irrigation water. In another lysimeter study, Greve *et al*. (2010*b*) demonstrated that deep drainage through irrigated Vertosols could persist even after the surface closure of macropores, due to the preferential flow of water through the still-open lower reaches of these same macropores. The combined

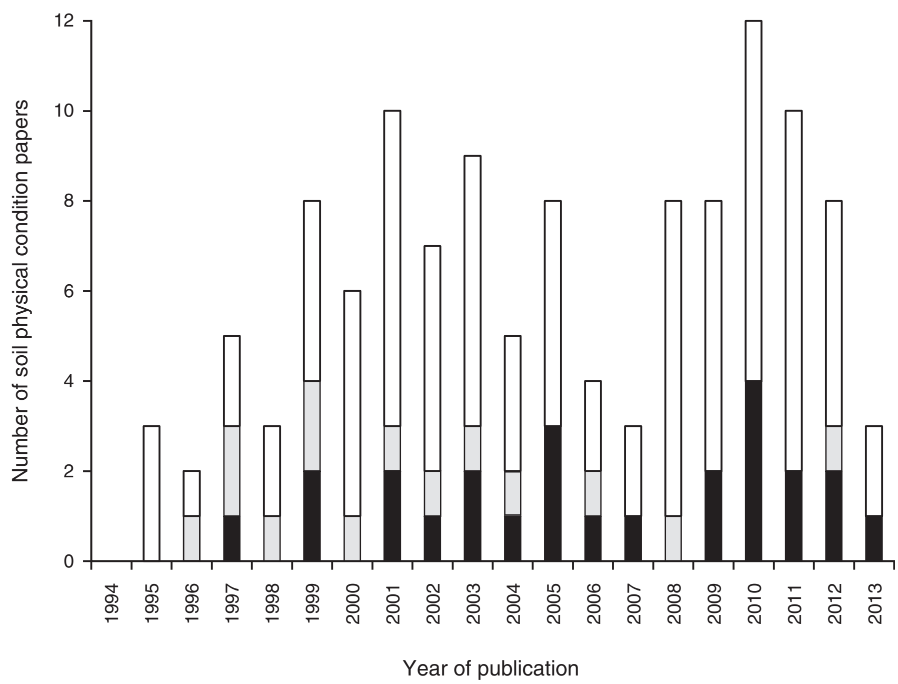

Fig. 2. The number of Cooperative Research Centre (CRC)-affiliated, peer-reviewed journal papers dealing primarily (black column) and secondarily (grey column) with soil physical condition published in each year of the CRC, and the total number of CRC-affiliated, soil-related papers published in each year (height of column).

results of these runoff and drainage studies show that various solutes and solids of significance to groundwater and surface water quality can be, and are, moved around the cotton-growing landscape, and that an environmental imperative remains to optimise crop water-use efficiency. While the flushing of salts from the soil profile through deep drainage might be viewed as a useful outcome for the cotton-grower, the transport of these salts to other parts of the landscape may merely be shifting the problem to other landholders and irrigators. Related research into deep drainage on dryland Vertosols in southern Queensland (e.g. Silburn *et al*. 2011; Tolmie *et al*. 2011) concluded that simply the removal of native vegetation was sufficient to mobilise salt stored in the soil profile, regardless of the crop or pasture regime implemented.

A final soil physical research focus of the Cotton CRC was the development of electrical resistivity measurement techniques to more accurately assess zones of rapid water movement in irrigated Vertosols. In a series of papers, measurements of apparent soil electrical resistivity were used to monitor the evolution of cracking in laboratory and field settings (Greve *et al*. 2010*a*), two-dimensional electrical resistivity tomography (imaging) was used to map the heterogeneity of soil profile water content across multiple furrows following irrigation (Kelly *et al*. 2011), and three-dimensional electrical resistivity tomography was used to assess water percolation into furrows with different surface cracking intensities (Greve *et al*. 2011). As noted in Greve *et al*. (2011), these resistivity techniques show considerable potential for further research into irrigation management, as time series measurements can quickly indicate if preferential flow is occurring under a given irrigation regime.

Salinity and sodicity

The strong reliance on irrigation for profitable cotton production in semiarid areas of eastern Australia has meant that research into the risk of salinity has been prominent during the life of the three cotton CRC. During the years of the CRC-SCP, salinity research effort was focussed on the development of EM induction and statistical techniques for assessing salinity risk across fields, and EM induction surveying of fields, farms and districts. By the time the AC-CRC commenced, this research had started to mature, leading to several papers dealing with the calibration of different EM devices to predict salinity and statistical methods for assessing and mapping salinity risk (Fig. 3) (Triantafilis *et al*. 2000, 2001*b*, 2002, 2003*b*, 2004*b*). These papers were based on experimental work carried out in the lower Namoi, Gwydir and Macquarie valleys, on fields of cotton farms and in specific landscape positions with presumed salinity issues. Geo-referenced soil electrical conductivity data, collected through the valley-wide mapping programs described earlier, were made available with some accompanying maps in the CRC soils database (Australian Cotton CRC 2004).

The transition to the Cotton CRC saw continued work on both the surveying of salinity in various locations and the development of models to more accurately predict EC depth functions using different EM devices. In the Bourke Irrigation District, Odeh and Onus (2008) conducted a field survey and then mapped topsoil EC using regression kriging, while Triantafilis and Buchanan (2010) estimated the spatial distribution of saline soil layers to a depth of 12 m using EM34 data acquired from across the district. A series of papers were also published (Triantafilis and Monteiro Santos 2009, 2010; Monteiro Santos *et al*. 2010; Triantafilis *et al*. 2013*b*) detailing methods of

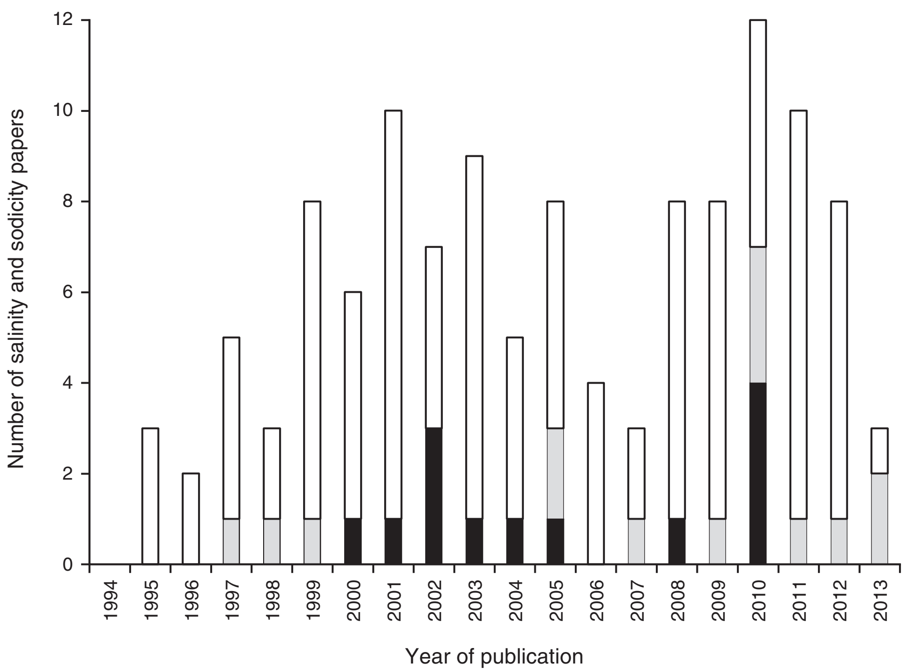

Fig. 3. The number of Cooperative Research Centre (CRC)-affiliated, peer-reviewed journal papers dealing primarily (black column) and secondarily (grey column) with salinity and sodicity published in each year of the CRC, and the total number of CRC-affiliated, soil-related papers published in each year (height of column).

analysing data output from the EM38, EM34, EM31 and DUALEM-421 devices to describe changes in EC through both the rhizosphere and soil horizons down to 30 m depth. These methodological papers used EM data collected during previous surveys in the Gwydir, Namoi and Macquarie valleys.

An over-arching conclusion that can be drawn from the extensive body of salinity research carried out in northern NSW over the life of the three cotton CRC, is that irrigation-induced salinisation is not a widespread problem in this region. Although natural salt stores are ubiquitous in the semiarid and arid landscapes of Australia, and irrigation inefficiencies may lead to deep drainage, the creation of shallow watertables and the mobilisation of stored soluble salts into the root zone, instances of such problems have been reported in only a few areas. In the Bourke Irrigation District, water storage reservoirs located on or adjacent to aeolian dune systems (Buchanan *et al*. 2012) drive deep drainage and the creation of shallow watertables (Triantafilis and Buchanan 2010). Owing to the presence of saline subsurface material associated with a Cretaceous marine mudstone (Triantafilis and Monteiro Santos 2011), isolated point source salinisation has resulted in this district. In the Trangie and Warren areas of the Macquarie valley, deep drainage (Willis and Black 1996) associated with the location of water storage reservoirs and supply channels (Triantafilis *et al*. 2004*a*) has similarly created isolated instances of shallow saline watertables leading to minor impacts on irrigated cotton production.

Although not as well known as a limitation to crop production as salinity, subsoil sodicity is a widespread problem across many semiarid and arid cotton-growing districts. In some situations, the landforming of cotton fields to optimise irrigation operations has resulted in the effective raising of highly sodic subsoil horizons closer to the soil surface (Cay and Cattle 2005). Large concentrations of sodium on exchange sites of clay mineral surfaces can lead to dispersion of clay aggregates upon wetting, and/or when subjected to mechanical disturbance. Resultant effects of soil dispersion include reduced hydraulic conductivity, increased bulk density, and a greater propensity for erosion. As a consequence, research into the plant and soil effects of sodicity has, to varying extents, been a common theme of all three CRC. During the years of the CRC-SCP, there were no papers published that specifically addressed the mechanisms of soil sodification or the distribution of sodic soil, but exchangeable sodium concentrations and ESP were routinely measured in many research projects investigating the effects of different crop rotations, tillage practices, residue management and soil amendments on soil quality and cotton yield (e.g. Hulugalle 1996; Hulugalle *et al*. 1996, 1997, 1998, 1999*a*, 1999*b*; Hulugalle and Entwistle 1997; Chan and Hulugalle 1999). General and consistent conclusions drawn from this body of work were that incorporating crop residues is more effective for decreasing soil ESP than mulching those same residues, and that minimum tillage practices and the use of rotation crops with cotton are significantly more effective for decreasing ESP than maximum tillage and/or continuous cotton production.

At an international sodicity conference held at Tatura, Victoria in early 2000, numerous sodicity knowledge gaps were identified for the cotton industry, including the better prediction of clay dispersion caused by sodicity, the effects of sodicity on cotton growth, soil processes in sodic soils, the effects of using sodic irrigation water, the economic and social costs of sodicity, the efficacy of sodicity ameliorants, and the effects of sodicity on soil biota (Surapaneni *et al*. 2002). In the following years of the AC-CRC and Cotton CRC, further work was carried out on the effects of different crop rotations and soil husbandry strategies on sodicity in various locations (e.g. Hulugalle *et al*. 2002*a*, 2002*b*, 2004, 2005, 2006, 2007; Cay and Cattle 2005; Hulugalle and Weaver 2005), and some of the gaps identified at Tatura were specifically addressed by research projects. Hulugalle and Finlay (2003) addressed the issue of the best sodium-based predictor of dispersion in cotton-growing Vertosols, and concluded that, due to the confounding effect of organic matter and other stabilising agents in soil, none of the commonly used sodium-related indices of dispersive behaviour (ESP; electrochemical stability index, ESI; EC/Exch. Na) were consistently accurate. In later work, Odeh and Onus (2008) echoed this finding by asserting that although ESI 'gave a good indication of dispersion' in their Bourke Irrigation District dataset, there were nevertheless discrepancies between ESI and ASWAT scores, and that other factors affecting soil structural breakdown warranted further investigation. Speirs *et al*. (2011) reinforced these earlier findings by concluding that irrigating red and black Vertosols with waters of different sodium contents caused varying dispersion effects due to differences in clay mineral suite and CEC between the soils; the red Vertosol, with less smectite clay and lower CEC, suffered a more dramatic loss of aggregation with increasingly sodic irrigation water, than did the black Vertosol.

The specific effects of sodium concentration on cotton plant growth were investigated by Dodd *et al*. (2010*a*, 2010*b*). In the first of these two papers, a method was developed to prepare soil samples of varying sodicities, but constant salinity, for glasshouse experimentation (Dodd *et al*. 2010*a*). This method was then used by Dodd *et al*. (2010*b*) to investigate the direct effect of sodium concentration on the growth of young cotton plants, without the confounding effect that high salinity might have on cotton growth. The results of this latter study indicated that the growth of cotton plants was unaffected by sodium concentrations up to those found in moderately sodic soil (ESP ~15), and that at low to moderate levels of sodicity, poor soil physical condition is a greater limitation to cotton growth than the direct chemical effect of sodium.

The efficacy of various amendments in ameliorating the effects of sodicity was investigated by Ghosh *et al*. (2010) and Hulugalle *et al*. (2010*a*). In the work of Ghosh *et al*. (2010), two sodic Vertosols were sampled, 'sodified' to three different levels of ESP in the laboratory and then subjected to 4-weeks' incubation following the application of cotton gin trash, cattle manure and composted chicken manure to each of the six different soil samples. After incubation, the treated soils were assessed for structural stability and clay dispersion. Ghosh *et al*. (2010) concluded that the application of these organic amendments was generally beneficial to soil physical condition, but that the effects were inconsistent across the two soils and three levels of ESP. In the field study of Hulugalle *et al*. (2010*a*), the ESP and structural stability of a sodic Vertosol were assessed 1 and 2 years after the application of manure, gypsum and potassium (K) fertiliser amendments. Although all three treatments lead to reductions in the subsoil ESP, the soil structural instability and crop yields were unaffected, leading Hulugalle *et al*. (2010*a*) to conclude that the application of these amendments at recommended rates to highly sodic soil in areas of erratic rainfall was unlikely to be effective or sustainable. Clearly, the use of amendments for reducing the negative impacts of sodicity is a complex issue, with factors such as extent of sodicity, soil EC, pH, OC content, rainfall/irrigation regime, cost of amendment and rate of amendment all interacting to produce different responses in different locations. Further research on this topic appears to be essential.

Soil chemical fertility

Although cotton-supporting Vertosols are generally regarded as being moderately to highly chemically fertile (McKenzie 1998), there are nevertheless a variety of production-related soil chemistry issues that have been investigated during the cotton CRC lifetime. Chief among these have been N dynamics under irrigated cotton production systems, P behaviour in Vertosols, K supply and micronutrient status. As shown in Fig. 4, papers primarily related to soil chemical fertility have rarely dominated the soil science paper output of the CRC, but notably, a large proportion of papers have secondarily addressed chemical fertility issues. The great bulk of this research work has been framed within the context of different cotton management regimes, including different crop rotations, different irrigation regimes, different tillage regimes and different strategies for dealing with cotton crop residues. Three long-term experimental sites, established on farms near Narrabri (Merah North) and Warren in NSW, and Dalby (Warra) in Queensland, were used extensively during the CRC-SCP and AC-CRC for this farming systems research. The review of Hulugalle and Scott (2008) gives a thorough account of how findings from this body of work have led to changes in soil quality and profitability of irrigated cotton production.

During the late 1990s and early 2000s, considerable work was carried out on nutrient (particularly N) dynamics and cotton yields under different cotton-crop rotations. In the majority of these studies, the commonly assessed soil chemical attributes included pH, EC, exchangeable cation concentrations, total OC content and nitrate-N content (e.g. Hulugalle and Entwistle 1997; Hulugalle *et al*. 1999*a*). Rotation crops investigated included wheat and legumes such as cowpeas, faba bean, soybean, field pea, vetches and dolichos (lablab). The outcomes of this body of research, with regard to the efficacy of such rotation crops in improving soil chemical fertility, were somewhat mixed. Although cowpeas in rotation with cotton were found to increase topsoil nitrate-N content by 23% relative to a period of fallow in a Namoi valley Vertosol, the subsequent cotton crop in the cowpea field yielded significantly less lint than that in the previously fallowed field (Hulugalle and Entwistle 1996). Similarly, a range of leguminous rotation crops were found to have only a limited effect on soil chemical attributes such as pH, exchangeable cation concentrations, sodicity and EC, in a sodic Vertosol of the Namoi valley (Hulugalle *et al*. 2002*a*). In contrast, the grain legumes faba beans and soybeans, and the leguminous green manure crops of field peas and lablab, were

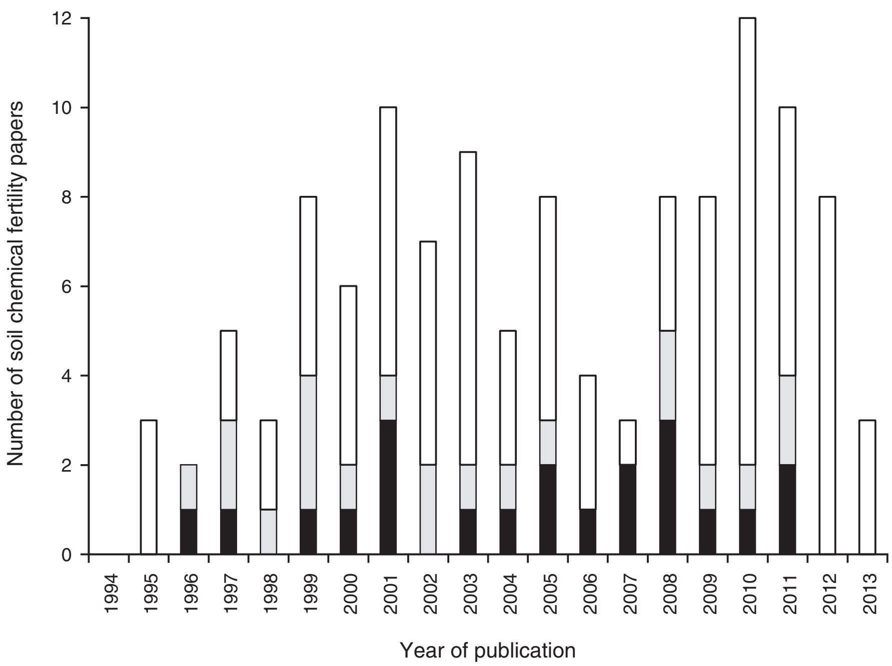

Fig. 4. The number of Cooperative Research Centre (CRC)-affiliated, peer-reviewed journal papers dealing primarily (black column) and secondarily (grey column) with soil chemical fertility published in each year of the CRC, and the total number of CRC-affiliated, soil-related papers published in each year (height of column).

found to fix considerable nitrate-N for the following cotton crops, resulting in a much lower required N-fertiliser addition to achieve optimum yields (Rochester *et al*. 2001*a*, 2001*b*). Vetches were also found to fix considerable N and improve the lint yields of following cotton crops (Rochester and Peoples 2005). Possible reasons for the somewhat inconsistent effect of leguminous rotation crops on following cotton crop yields include allelopathic effects of some legumes on cotton (Hulugalle and Scott 2008), the harbouring of pathogens in legume residues (Hulugalle *et al*. 1999*a*), very short residual effects of the legume where the residues are not recalcitrant (Hulugalle *et al*. 2006) and the over-riding influence of soil physical condition in some locations (Hulugalle *et al*. 2001*a*). For farming systems where the supply of water is not limiting, Peoples *et al*. (2001) asserted that the amount of atmospheric N_2 fixed by legumes is regulated by biomass production, suggesting that soil N status is enhanced by growing larger legumes and not exporting the biomass from the field. One of the general conclusions of Hulugalle and Scott (2008) is that leguminous rotation crops improve the overall soil N balance, whereas wheat rotation crops are effective at recycling N leached below cotton's root zone and promoting the leaching of excess salts.

Other aspects of N fertility of cotton soils investigated during the CRC-SCP and AC-CRC were those of N uptake efficiency and denitrification losses. A comparison of fertiliser-N uptake by cotton following stubble retention or stubble burning (Rochester *et al*. 1997) revealed that, over several seasons, the retention of stubble rather than its removal led to more efficient uptake of fertiliser-N by cotton and greater lint yields. Where excess N-fertiliser application had resulted in leaching of N into the subsoil under irrigated cotton, Hulugalle (2005) demonstrated in a Namoi valley field study that a following wheat crop could be used to recover some of this leached N and return an enhanced yield. The efficacy of nitrification inhibitor chemicals in decreasing fertiliser-N losses was tested by Rochester and Constable (2000) in a laboratory study, with the main finding being that the most effective inhibitor, etridiazole, suppressed denitrification losses by suppressing the supply of nitrate. The environmental importance of denitrification losses of N from irrigated, alkaline Vertosols was further explored by Rochester (2003), who estimated that ~1% of N fertiliser applied to an irrigated cotton crop would be lost as N_2O gas following denitrification. Although this proportion of N_2O gas emission is relatively small, the substantial contribution of N_2O to the global greenhouse effect makes the efficient application and uptake of fertiliser-N an on-going environmental imperative for the cotton industry. In recent work, Rochester (2011*a*) calculated that typical commercial cotton farming rates of N fertiliser are ~50 kg N/ha in excess of the plant requirement, representing a substantial pool of N that may contribute to the global greenhouse effect.

The P nutrition of cotton grown in Vertosols was subjected to some scrutiny during the AC-CRC and Cotton CRC. Although N has been the dominant nutritional input in traditional Australian cotton systems (Dorahy *et al*. 2004), the observation that increasing numbers of cotton growers were becoming concerned about declining soil chemical fertility after 20–30 years of cotton production necessitated an investigation of soil P status. Research into P uptake by cotton crops in the Gwydir, Macintyre, Macquarie and Namoi valleys indicated that soils containing at least 8.5 mg/kg of Colwell-extractable P in the top 0.3 m of the profile did not require P fertilisation (Dorahy *et al*. 2004), and that most of the Vertosols tested in these valleys for this work exceeded that level. In contrast, the Vertosols of the Ord River Irrigation Area of north-western Western Australia were found to be deficient in P (2–3 mg/kg of Colwell-extractable P), and that cotton crops required substantial applications of P fertiliser to achieve maximum yield (Duggan *et al*. 2008). The related issue of poor P-use efficiency of cotton was also investigated (Dorahy *et al*. 2007, 2008) as a possible reason for the lack of response of some cotton crops to applied P fertiliser in fields with only moderate levels of plant-available P. Results of this work, however, indicated that the majority of the fertiliser P remained in a plant-available form for some weeks or months after application, and that fixation or occlusion of the applied P was not a significant problem for these alkaline Vertosols. Instead, it appears that soil sodicity may play a role in suppressing P uptake in cotton, even when there is sufficient plant-available P present in the soil; the study of Rochester (2010) demonstrated that crop P uptake was reduced by almost a quarter in sodic soils compared with non-sodic soils, while crop sodium uptake was more than doubled.

The mechanisms of, and factors affecting, P uptake by cotton from Vertosols was further investigated in a series of papers by Wang *et al*. (2007, 2008, 2009, 2011). After describing the various pools of P present in a black Vertosol of southern Queensland and demonstrating that crops extract P from all depths down to 30 cm regardless of fertiliser application depth (Wang *et al*. 2007), the possibility of cotton roots using hydraulic lift of subsoil water to the drier topsoil to aid in the accessing of topsoil P was investigated by Wang *et al*. (2009). They found that although cotton plants could hydraulically lift water in clayey soil, it did not aid P uptake from the surface soil horizon. In another rhizobox study, Wang *et al*. (2008) demonstrated that cotton plant roots were relatively inefficient physiologically in absorbing inorganic forms of soil P, in comparison to wheat and white lupin. A follow-up study confirmed that cotton is also inefficient in using sparingly soluble P applied as a fertiliser (Wang *et al*. 2011). These findings provide a further explanation for the lack of response of some cotton crops to applied P fertiliser noted by Dorahy *et al*. (2007, 2008), and suggest that growing cotton on P-deficient soils is an inefficient and potentially unsustainable enterprise.

The K supply in Vertosols was investigated sporadically during the cotton CRC lifetime. Although exchangeable K concentrations were routinely measured in the bulk of the cotton cropping systems research carried out (e.g. Hulugalle and Entwistle 1997; Hulugalle *et al*. 2005; Weaver *et al*. 2013), rarely was K the focus of this research. An early exception to this was the paper of Wright (1999), which reported that the supply of K appeared to have a role in causing premature senescence of some cotton crops. A subsequent CRDC-funded PhD project (Bedrossian 2005) concluded that there was not a consistent and direct relationship between soil K supply and premature senescence, but that K was nevertheless a contributing factor. Thereafter, several papers appeared that detailed the uptake of soil K by cotton plants in different environments, including northern Australia (Duggan *et al*. 2008) and eastern Australia (Rochester 2007, 2010). In the Ord River Irrigation Area of northern Australia, cotton plant uptake of K was strongly correlated with the uptake of P in the P-deficient soils there (Duggan *et al*. 2008), while in a wide-ranging comparison of soils from across northern NSW cotton-growing valleys, Rochester (2010) found that cotton plant K uptake was suppressed in sodic soils, regardless of the available K concentrations in the soil. Applications of K fertiliser to the sodic soils did not elicit a cotton yield response, even though Rochester (2007) demonstrated that the average rate of K export with a cotton crop is second only to N.

For some time it has been understood that the cotton micronutrient most likely to be deficient in the alkaline Vertosols of eastern Australia is zinc (Zn) (Constable *et al*. 1988). Although only relatively small amounts of Zn are taken up by cotton (60 g/ha) compared with other micronutrients such as iron, manganese and boron, it is taken up by cotton throughout the season and its availability can be diminished by waterlogging (Constable *et al*. 1988). Similar rates of Zn uptake by cotton were measured by Duggan *et al*. (2008) in northern Australia, with Zn deficiency observed under conditions of P deficiency. In a study of cotton nutrient uptake and export from a Namoi valley Vertosol with a history of crop response to N and Zn fertilisers, Rochester (2007) calculated that ~70% of Zn taken up by cotton plants was exported from the field in the seed, leading to the conclusion that while 'micro-nutrients normally pose few problems in these soils', the replacement of exported Zn was achieved by 'applying zinc sulfate at 1 kg/ha every one to five years'.

Soil carbon and biota

Although the amount of research into soil organic carbon (SOC) has exploded in recent times due to the emergence of the 'carbon economy' and a recognition of the importance of soil C sequestration in an era of climate change (e.g. Janzen *et al*. 2011), research into organic components and biota of cotton-growing soils has been common to all three cotton CRC (Fig. 5). The role of organic matter in maintaining soil quality through effects on soil structure, nutrient availability and populations of soil biota (e.g. Loveland and Webb 2003) has meant that measurement of SOC has been deeply embedded in much CRC research. During the years of the CRC-SCP, when soil research paper output was dominated by soil C and biota-related papers (Fig. 5), considerable research effort was dedicated to the development of a method for fractionating labile and non-labile soil C pools (Blair *et al*. 1995), and the subsequent calculation of a C management index. A series of papers followed (Conteh *et al*. 1997, 1998; Conteh and Blair 1998) documenting labile and non-labile C components in cotton-growing soils (and adjacent uncultivated soils) of various valleys in NSW and Queensland, the distribution of these C pools in different aggregate size fractions in the soil, and the effects of different stubble management strategies on these C pools. Key findings of this work were that cultivation had caused a pronounced decrease in labile soil C contents, that most of the OC present

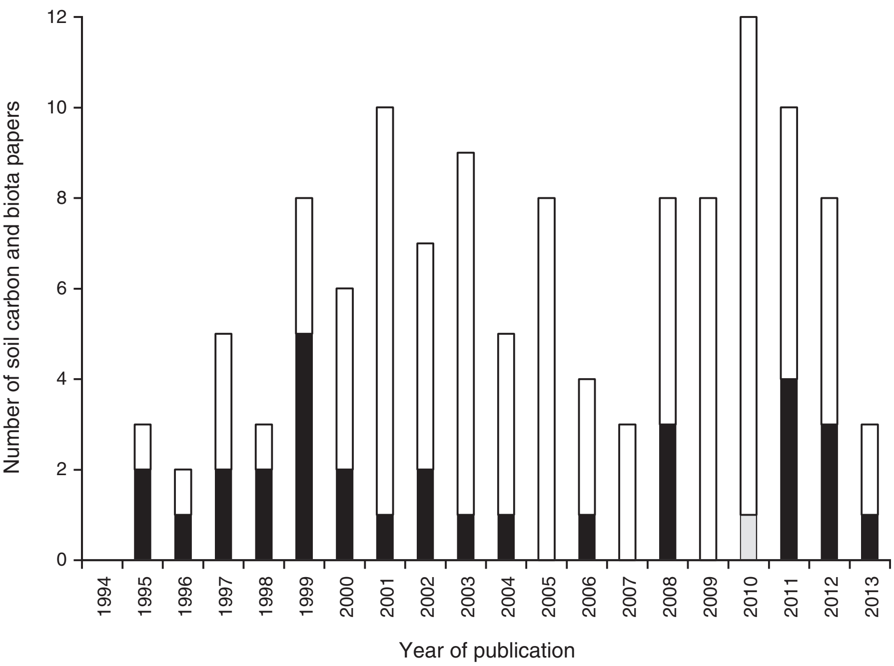

Fig. 5. The number of Cooperative Research Centre (CRC)-affiliated, peer-reviewed journal papers dealing primarily (black column) and secondarily (grey column) with soil carbon and biota published in each year of the CRC, and the total number of CRC-affiliated, soil-related papers published in each year (height of column).

in Vertosols was concentrated in microaggregates, and that stubble burning lead to substantially lower SOC contents than stubble incorporation.

At much the same time, a range of other research projects investigating the effects of different crop rotation strategies on Vertosol physical and chemical properties also involved the monitoring and measurement of soil C status (e.g. Hulugalle 2000; Hulugalle *et al*. 1997, 1999*a*, 2001*a*, 2002*a*, 2005), generally through the use of the wet oxidation Walkley and Black method. As surmised by Hulugalle and Scott (2008), the bulk of these studies indicated that regardless of the choice of rotation crop, in the short-term SOC contents tended to remain unchanged or decrease in cotton production systems, but that any decrease was greater under cotton monoculture. In some cases, although SOC content was unchanged or decreased somewhat, rotation crops were found to have a stimulatory effect on soil biotic activity, including improved mycorrhizal colonisation of cotton roots (e.g. Hulugalle *et al*. 1999*a*). A study of the total soil C pool (to a depth of 0.9 m) in a 128-ha cotton field in the Gwydir valley (Knowles and Singh 2003), and a small number of nearby native vegetation sites, indicated that topsoil SOC contents had been reduced by ~60% due to clearing and 25 years of cropping with a cotton-cotton-wheat rotation.

The particular importance of tillage regimes on SOC sequestration was examined in several studies, including some of those (above) investigating rotation crop effects (e.g. Hulugalle *et al*. 1997, 1998, 2004, 2005). In most of these studies, conventional (intensive) tillage regimes were found to result in lower SOC contents than minimum tillage regimes, and in some cases (e.g. Hulugalle *et al*. 2005) the differences in SOC contents were clearly greater between tillage systems than between continuous cotton and cotton-wheat rotation systems. A comparison of SOC contents under long-fallowed soil and soil subjected to continuous cotton with intensive tillage (Hulugalle *et al*. 1998), revealed that both treatments led to a decline in SOC content over a period of several years. The main conclusion of Hulugalle (2000) was that the best prospect for SOC sequestration in cotton production systems was presented by long-term (>10 years), cotton-wheat rotation systems incorporating minimum tillage practices.

During the Cotton CRC the focus of SOC research started to shift from a dominantly production emphasis to a more environmental emphasis. With the emergence of estimates of substantial greenhouse gas emissions under irrigated cotton production (e.g. Maraseni *et al*. 2010), and the possibility of agriculture being included under C pollution reduction schemes in the future, the sequestration of C in cotton soil had taken on a still greater relevance. After the sobering findings of Knowles and Singh (2003) regarding the loss of SOC under irrigated cotton systems of the preceding 25 years, the findings of a 10-year SOC monitoring study by Rochester (2011*b*) came as a welcome counter-point. In this study, the SOC sequestered under five different cotton-based, minimum-till cropping systems, including wheat, vetch, faba bean and fallow periods between cotton crops, ranged from 1.1 to 3.8 t C ha^{-1} $year^{-1}$, to a depth of 0.9 m. More SOC was sequestered in those cropping systems including a legume, and the subsurface zone of the profile (0.3–0.6 m depth) received the bulk of the sequestered C, but importantly, all of these cropping systems resulted in more C sequestration than the estimated emissions of CO_2 from an irrigated cotton cropping system (Rochester 2011*b*). Measurements of C inputs into soil from wheat and vetch roots by Hulugalle *et al*. (2012*b*) indicated that the leguminous vetch was a more effective rotation crop for sequestering C from roots, but in another field study run over a 6-year period, Hulugalle *et al*. (2012*c*) found that a cotton-wheat rotation out-performed a cotton-vetch rotation in terms of maintaining soil quality attributes, and that inclusion of the vetch in the cotton-wheat rotation did not significantly improve cotton yield or reduce CO_2 emissions. The extra farming operations involved in growing vetch partly offset the small amount of extra CO_2 fixed by the crop. Clearly, the C-sequestration potential of certain rotation crops is not the only criterion for adoption in modern cotton-growing systems.

An aspect of soil C research that received attention during both the CRC-SCP and Cotton CRC was that of the use of organic amendments in cotton production systems. In the late 1990s, Hulugalle (1996) conducted an incubation study to investigate the effects of applying pelletised sewage sludge to a Vertosol topsoil, and concluded that significant short-term effects were wrought on chemical properties, but not on physical properties. A decade later, over a series of several papers, Ghosh *et al*. (2008, 2010, 2011*a*, 2011*b*) reported the results of field and incubation experiments involving the application of a range of organic amendments, including cattle manure, composted cotton gin trash, vermicompost, composted chicken manure and biosolids, to cotton-growing Vertosols. The results reported were mixed; application of these amendments at ‘low’ rates generally had little short-term effect on soil properties or cotton production, while at larger application rates different amendments improved different soil attributes, including nitrate-N concentrations, K availability and microbial biomass. Perhaps tellingly, the greatest benefits derived from organic amendment application occurred in the most sodic Vertosols used in these experiments, suggesting that organic amendments might be best targeted at poorer quality soils.

In their review of the use of organic amendments in Australian agriculture, Quilty and Cattle (2011) concluded that although organic amendments are unlikely to supercede synthetic and inorganic amendments in broadacre agricultural enterprises, they are likely to become an increasingly important component of sustainable, modern cropping systems because of the range of beneficial effects they can construe on soil condition and plant production. However, Quilty (2011) also trialled the use of a variety of organic amendments on cotton-growing soils of the Lachlan and Macquarie valleys, and found little short-term effect of amendment addition, especially at lower application rates. It is clear that further research is needed to identify how organic amendments can be effectively and affordably incorporated into cotton production systems, with the questions of longevity-of-effect and optimal application rate being paramount.

The presence and role of soil biota in cotton production systems has also been researched throughout the cotton CRC lifetime. Early work (Hulugalle 1995) identified that ants, through the construction of ant hills in cotton fields, can have a minor effect on Vertosol physical and chemical properties by accumulating comparatively coarse-grained mineral and organic particles. Subsequently, Nkem *et al*. (2000) demonstrated that abandoned ant hills may act as a long-term source of nutrient release into the surrounding soil, while Nkem *et al*. (2002) reported that ant activity in cotton-wheat rotation systems was heavily influenced by season, and generally less than that in nearby native vegetation sites. The seasonal abundance of springtails, beetles, ants and earwigs in cotton-growing soils of northern NSW was documented by Lytton-Hitchins (1998), while McGee *et al*. (1997) investigated the survival of arbuscular mycorrhizal fungi (AMF) in soil under pasture and soil under irrigated cotton. These fungi are important symbionts of cotton roots, as they enhance the uptake of plant nutrients such as P and Zn, and McGee *et al*. (1997) concluded that although severe disturbance such as cultivation might diminish the presence of the fungi, enough viable propagules remained to re-colonise the following cotton crop. Later, Knox *et al*. (2008) demonstrated that genetically modified cotton plants expressing insecticidal traits could form symbioses with AMF just as effectively as conventional cotton lines. Soil conditions promoting the activity of cotton plant pathogens have been investigated from time-to-time as outbreaks of disease have occurred, with root browning associated with a growth disorder (Nehl *et al*. 1996), fusarium wilt (Wang *et al*. 1999*a*, 1999*b*), and black root rot (Hulugalle *et al*. 2004) being three prominent examples. Other research groups have identified and characterised populations of plant parasitic nematodes (Knox *et al*. 2006), archaea (Midgley *et al*. 2007*a*), and basidiomycetes (Midgley *et al*. 2007*b*) that inhabit Vertosols under cotton production systems in eastern Australia.

A final area of CRC research related to the biota of cotton production systems is that of pesticide interactions in soil. During the CRC-SCP in particular, work was carried out to determine the potential for microbes to breakdown herbicides in cotton-growing soil (Van Zwieten and Kennedy 1995), and the sorption and desorption characteristics of commonly-used herbicides in cotton soils with different SOC contents and clay mineral suites (Baskaran and Kennedy 1999). In a novel and cross-disciplinary piece of work, Shivaramaiah *et al*. (2002) effectively combined pesticide chemistry with the soil survey effort of the cotton CRC to estimate the distribution of DDT residues in several cotton-growing valleys; this work utilised enzyme-linked immunosorbent assays of previously collected topsoil samples and GIS techniques to map DDT residue concentrations at the catchment scale. Later, under the auspices of the Cotton CRC, Weaver *et al*. (2012) investigated the presence of pesticide residues in Namoi valley Vertosols down to a depth of 1.2 m, and found trace amounts of some pesticides at depth in some locations, despite the fact that some of these had not been used for 20 years.

Soil science extension and education

Prior to the advent of the CRC-SCP, the soil extension effort for the cotton industry had been focussed on the production of the first two SOILpak editions (Daniells and Larsen 1990, 1991). As discussed in Daniells *et al*. (1996), these early SOILpaks were strongly focussed on soil structure, and on the identification and remediation of compaction, in particular. Guidelines for best practice soil management to overcome compaction had been gathered ‘from researchers, agronomists and leading growers’ (Daniells *et al*. 1996), and the SOILpaks promoted around the cotton industry through workshops. Towards the end of the CRC-SCP, the third edition of SOILpak (McKenzie 1998) was released as a comprehensive decision support manual containing information on managing soil for cotton production, diagnosing problems with soil condition, and improving soil condition after diagnosis of problems. The third SOILpak included ~320 listings of resource materials (including peer-reviewed journal articles, conference proceedings, magazine articles, technical reports and personal communications), with many ‘inherited’ from the first two editions. Of these listed resource materials, around 70 were peer-reviewed journal articles, and of those, only seven listings referred to journal papers published under the auspices of the CRC-SCP. However, a significant number of CRC-affiliated researchers were cited for conference presentations and articles in popular magazines such as *The Australian Cottongrower*, which were generally written in a much more accessible style for growers and agronomists. In

Table 1. Soil-related PhD projects funded and/or administered by the cotton CRC

CRC	Number of PhD completed	Number of soil science-related PhD completed	PhD topic
CRC-SCP (1994–99)	15	3	Lytton-Hitchins (1998) – soil fauna Field (2000) – aggregation in Vertosols Dorahy (2002) – P nutrition of cotton
AC-CRC (2000–05)	14	5	Montgomery (2003) – soil water balance Stewart (2003) – site-specific N management Bedrossian (2005) – soil K supply for cotton Speirs (2006) – sodic soil structural stability Buchanan (2006) – hydrology of Bourke irrigation district
Cotton CRC (2006–12)	48	7	Dodd (2007) – cotton growth in sodic soil Loke (2007) – AMF ecology in cotton soils Vanags (2007) – palaeochannel hydrology Whiffen (2007) – AMF, soil C sequestration Greve (2009) – subsurface cracking of clays Bennett (2011) – sodic soil amelioration Quilty (2011) – organic amendments to soil

many cases, the concepts, findings and recommendations presented in these non-peer-reviewed media would be, or already had been, published as peer-reviewed articles.

In the early 2000s, the stable of 'paks' for the cotton industry mushroomed, and certain parts of SOILpak were adapted and expanded upon in other paks, most notably NUTRIpak (Rochester 2001) and WATERpak (Cotton Research and Development Corporation 2004). Again, there were not large numbers of CRC-funded or affiliated, peer-reviewed, soil science articles referred to in these paks, but other outputs of CRC-affiliated researchers were prominent. Similarly, in 2008, with the launch of the CottASSIST suite of online decision support tools, the NutriLOGIC tool allowed growers to estimate optimal fertiliser applications based on relationships between soil and plant nutrient status developed by CRC researchers. The first 3 years of the Cotton CRC also saw a concerted 'on-the-ground' soil extension effort, with Healthy Soils Symposiums held in Narrabri, Goondiwindi and Hillston, 15 Healthy Soils Training Workshops held across the industry, and a series of case study and demonstration sites established. To varying extents, these initiatives involved the collaboration of a variety of government, educational and industry stakeholders. More recently, research into the role of soil science extension in the adoption of soil health improvement strategies by Macquarie and Lachlan valley farmers was conducted by Bennett and Cattle (2013*a*, 2013*b*). They concluded that although existing extension programs needed to be somewhat more targeted, these extension programs were nevertheless an important incentive for farmers to pursue soil health improvement strategies. As the third edition of SOILpak is now some 15 years old, there is a strong case for this successful extension tool to be updated with a fourth edition, including relevant findings from AC-CRC and Cotton CRC research. Similarly, more recent research findings could also be used to update the soil health module of the cotton industry's on-line best management practice (myBMP) program for growers.

The role of the cotton CRC in education, including in soil science, was discharged in three discrete ways; (*i*) the funding of PhD scholars, (*ii*) the funding of Summer Scholarship and Honours projects for undergraduate students, and (*iii*) the support of the University of New England Cotton Production Course. As shown in Table 1, the funding and completion rate of PhD scholars was greatest in the Cotton CRC, but the proportion of soil science-related PhD projects was greatest during the years of the AC-CRC (~35%), and between 15 and 20% for the other two CRC. The completed PhD listed in Table 1 covered all five categories of soil science reviewed above, viz. soil mapping and characterisation, soil physical condition, salinity and sodicity, soil chemical fertility, and soil C and biota, and many of them gave rise to peer-reviewed journal papers.

The funding of Summer Scholarship projects for year undergraduates was established during the AC-CRC and continued into the Cotton CRC. Sixty-five summer scholarships were awarded during these two CRC, including 38 during the Cotton CRC (Cunningham and Jones 2012). A further 15 Honours projects were also funded during the Cotton CRC. Although many of these summer scholarship and Honours projects were focussed on cotton agronomy and insect issues, there were a small number of more soil-focussed projects carried out under the auspices of this program, and some of these led to peer-reviewed journal papers (e.g. Cay and Cattle 2005; Vervoort and Annen 2006).

The University of New England Cotton Production Course was established in 1994 with the CRC-SCP, and has seen ~190 students successfully graduate (Cunningham and Jones 2012). Staffed by a CRC-funded lecturer, and with contributions to classes from other CRC researchers, the course includes a dedicated topic on soils, and discusses the interaction of soil properties with cotton nutrition, irrigation practices and precision agriculture. Although material from SOILpak is prominent in the course manual, only a handful of CRC-affiliated journal papers appear or are cited there (e.g. Rochester *et al*. 2001*a*; Tennakoon and Milroy 2003). Nevertheless, like the SOILpak itself, it is clear that the soil science research output of CRC researchers has informed much of the soil-related content of the cotton production course as it has developed.

Conclusions

The three successive CRC dedicated to the Australian cotton industry, spanning the years 1994–2012, allowed a coordination of research effort between the CSIRO, state government departments, universities, and cotton industry organisations and stakeholders. A common research strand in each of the three CRC was that of soil science, particularly of Vertsols, the main soil type used for irrigated cotton production in Australia. Over the 18 years of the CRC, ~120 CRC-affiliated, soil-related journal papers were published, and 15 PhD theses completed. These outputs dealt with both basic soil science research issues and very applied, cotton production-focussed issues, allowing both the discipline of soil science and the best management of cotton production, to advance. As the years passed during the three CRC, there was a perceptible shift in research priority from production-driven projects to environment-driven projects, but the soil research legacy of the cotton CRC will be a better understanding of Vertosols from both production and environmental standpoints. Particular strengths of the soil research program to emerge from the cotton CRC include: significant advances in soil property sensing and mapping methodologies for catchments, farms and fields; a wealth of information on the effect of different cotton production systems on the physical and chemical fertility of Vertosols; a better understanding of the threat of salinity and sodicity to sustainable cotton production in eastern Australia; early and sustained investigation into the SOC status and attributes of Vertosols; and measures of environmental impacts of cotton production, including deep drainage, solute transport in the landscape, and greenhouse gas emissions.

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