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Cotton Research and
Development Corporation

FINAL REPORT 2015

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Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

CRDC Project Number: UNE1201

Project Title: Positioning growers to take advantage of future ecosystem service markets

Project Commencement Date: 01/04/12 **Project Completion Date:** 01/07/15

CRDC Research Program: 2 Industry

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Date Submitted: 21/12/15

Part 3 – Final Report

(The points below are to be used as a guideline when completing your final report.)

Background

1. Outline the background to the project.

According to the Australian Grown Cotton Sustainability Report (2014), the average Australian cotton farm incorporates approximately 42% native vegetation, while more than half of the cotton farms surveyed incorporated an average of nine kilometres of river frontage and riparian lands. The area of cotton production is relatively small compared to other land uses in cotton-growing catchments. However, collectively, cotton farmers are responsible for the management of many thousands of kilometres of riparian lands that are essential for biodiversity conservation in the semi-arid and subhumid landscapes where cotton is grown (Hamilton et al. 2015; Lee and Rotenberry 2015; Naiman and Décamps 1997).

Ecosystem services are the benefits we, as humans, get from the environment. Many ecosystem services are directly relevant to cotton production, including natural pest control, nutrient cycling, water filtration and bioremediation of residues (Reid et al. 2003). Provision of many public good ecosystem services generated on cotton farms can attract monetary benefits through markets (e.g. carbon sequestration) or incentive programs (e.g. biodiversity conservation). Other ecosystem services cannot be valued in an economic sense, including most cultural services, but provision or protection of these services forms part of a growers' social license to farm.

This project at two dominant agendas, firstly, to benchmark biodiversity and vegetation condition across the industry and secondly, to provide data that could be used by growers and the industry to inform best practice management of native vegetation and riparian lands. The project was born out of Rhiannon's PhD research into ecosystem services provided by native vegetation on the lower Namoi floodplain. Rhiannon's thesis was one of the first studies in the world to measure (1) provision of multiple ecosystem services in several ecosystems over a large region; (2) the effects of native vegetation management on ecosystem service provision, and (3) explore the interdependence of multiple services and potential trade-offs or synergies between services. Rhiannon's thesis was also one of the first studies to explore vegetation condition in relation to ecosystem service provision and articulate targets for management to maximise vegetation condition for ecosystem service provision in various ecosystems.

Since this project commenced, a number of policy developments have occurred that have provided options for growers in terms of native vegetation management for ecosystem service provision. Most notably, we saw the first two auctions under the Federal Government's Emissions Reduction Fund and an average dollar-value of $13.12 per tonne put on carbon. A third auction is to be held early in 2016. While the dollar value set previously will not be attractive to many growers, especially given the value of arable floodplain cropping country, for marginal lands where cropping is not viable (e.g. flood-prone land, unsuitable soil types, etc.), carbon sequestration may be an attractive option. Future developments in this space should see an improvement in the price on carbon given international initiatives to lower greenhouse gas production and minimise climate change impacts.

Objectives

2. List the project objectives and the extent to which these have been achieved, with reference to the Milestones and Performance indicators.

This project had the following objectives:

1. Establish sites across most cotton catchments

In Spring 2012, 250 sites were established on cotton farms from Emerald to Darlington Point. Not all cotton-growing regions were included in the study due to weather and time constraints or reluctance of growers to participate in the study. However, we are satisfied that the major vegetation types encountered on cotton farms across the extent of the industry have been represented here. Vegetation types included were river red gum forest/woodland, coolibah, black box and belah woodlands, myall, brigalow and chenopod shrublands, grasslands and plantings. Sites were marked with steel fence posts and GPS points, and represent a benchmark vegetation condition in 2012. Sites could be resampled in future assessments of vegetation change on cotton farms. Environmental data and condition assessments were conducted at the time of site establishment, and a site management history was provided by each landholder.

2. Measure the carbon storage value of native vegetation on cotton farms

Carbon inventories were conducted at all sites, including above-ground woody biomass, herbaceous biomass, coarse woody debris, litter mass and soil carbon (at most sites) to 30 cm depth. A lengthy (and well-underestimated) lab time was required to process all the soil samples prior to carbon analysis by a commercial lab. A paper was published *in Crop and Pasture Science* on the carbon storage value of native vegetation on the lower Namoi floodplain. We plan to publish a further data based on the entire data set at a later date.

3. Provide data for cotton conference presentation and paper on C-neutral cotton farms and a journal article on carbon sequestration by native vegetation on cotton farms.

A literature review was conducted to determine carbon sequestration rates for relevant vegetation types on cotton farms. A case study on ‘Redbank’ was developed after a site visit prior to the conference, and with the help of Francois Visser at UQ, the case study reported a whole-of-farm carbon account. The case study showed this particular cotton farm was sequestering a large amount of carbon in native vegetation, and this was offsetting and more, the emissions from crop and livestock grazing enterprises. A speed talk was presented at the 2014 Cotton Conference. Since the conference, a second case study has been developed on ‘Wyadrigah’ near Mungindi which has again shown that cotton farms can be carbon neutral, particularly where areas of riparian vegetation exist on farm. A paper that reports the carbon sequestration value of riparian vegetation dominated by river red gums has received CRDC approval prior to submission to *Agriculture and Forest Meteorology* or *Forest Ecology and Management*. This paper will be submitted to a journal by the end of the year.

4. Measure the erosion mitigation value of native vegetation on cotton farms

A total of 9000 soil samples were collected for both carbon and aggregate stability measurements across the 250 sites. Of these, the surface portion (0–5 cm) and subsurface portion (20–30 cm) from each soil core was subjected to wet sieving analysis using machines borrowed from ANU and CSIRO Canberra (methods detailed below). A paper was published showing a relationship between soil carbon and aggregate stability in *Agriculture Ecosystems and Environment* using samples from the lower Namoi that were processed and analysed during this project. A final draft version of a paper reporting carbon–aggregate stability relationships on four vertosols encountered across the cotton growing regions is yet to come as there are a number of conflicting opinions of co-authors on statistical analysis of the data and framing of the paper.

5. Measure the erosion mitigation value of vegetative growth forms on cotton farms

This analysis was conducted at the same time as objective 4. The results from this study are likely to be rolled into the above paper due to the way the data was analysed. However, discussions continue and the final form of papers on this subject will be decided as writing progresses

6. Measure the biodiversity conservation value of native vegetation on cotton farms

Two spring vegetation surveys were conducted at 250 sites during this project. These surveys included assessments of herbaceous and woody vegetation, and the percent cover of each species encountered. The first survey was conducted in spring 2012 in what could be considered a ‘good’ or ‘average’ season, while the second survey was conducted in spring 2014 during a ‘poor’ or ‘very poor’ season in the central regions (St George/Dirranbandi, Goondiwindi/Boggabilla, Gwydir and Namoi. In addition, two birds surveys were conducted at each site in spring 2014 with the assistance of Dr Julian Reid (ANU), Dr Laura Scott (from Mexico) and Mr Stuart Green (UNE). A paper is flagged for publication from this data and has been written into a subsequent FRP for finalisation in 2016. Ideas for additional papers have been workshoped with co-authors and will be investigated in coming months.

7. Document variability in ecosystem service provision through time

Repeat vegetation and bird surveys, carbon accounting assessments and aggregate stability assessments were completed at Rhiannon’s PhD sites in the lower Namoi. A paper has been flagged for publication in 2016 on variability in plant and bird diversity between survey periods and has been written into a subsequent FRP. The bird data has been analysed and is ready for write up, and a paper on this subject has been commenced with Dr Julian Reid as lead author.

8. Develop calculators of ecosystem service provision in different vegetation types, condition states and management history

Data generated in this project, including relationships between ecosystem service provision and a range of environmental and management variables have been/will be published for each of the ecosystem services. A paper has been published on aggregate stability relationships with organic carbon in grey/brown vertosols, with plans for a paper on other soil types once data analysis issues have been sorted. A paper is currently awaiting approval from CRDC for publication on carbon sequestration rates by river red gums in different landscape situations (riparian vs floodplain) in various condition states. Data presented in this paper and the information obtained from the literature review conducted for the C neutral cotton farms case studies will be incorporated into the carbon calculators currently under development by Francois Visser and others. Papers already published plus the two biodiversity papers will report relationships that calculators will be based on. Once the relationships and data have been peer-reviewed, it can be included in calculators. We envisage this is an ongoing process and will work with BMP extension officers to put these calculators into a user friendly form.

9. Conduct interviews with landholders and experts and visit sites in the Namoi and Gwydir catchments to eliminate potential causes of eucalypt dieback, prepare and deliver a literature review on the causes of eucalypt dieback in the lower Namoi and Gwydir catchments to water users groups, and prepare and deliver an assessment of river red gum usage of ground and surface water

Conversations were conducted with landholders and experts informally to discuss potential causes of river red gum dieback in the Namoi and Gwydir catchments. These conversations have been documented and will be included as an appendix in the literature review. The literature review has been completed and includes a number of pieces of empirical data that has been collected through various studies. The review document is currently being formatted according to the new UNE publications template and will be sent to CRDC for approval prior to publication in early January 2016. A paper will be published on the causes of river red gum dieback, incorporating the literature review outcomes as part of a subsequent FRP. Bothe the literature review and paper will include the data on the use of surface and ground water by river red gums at one point of time (January 2014).

An illustrated short document outlining different causes of dieback was produced with help from Stacey Vogel and was commented on by Jane Trindall, prior to being sent to the GVIA. Information coming from Sam Capon's research into tree regeneration was also included in this document. To our knowledge, feedback has not been received from GVIA on this document. An extension document on river red gums was also produced for the CottonInfo website. A paper has recently received CRDC approval for publication and documents the impact of dieback on carbon sequestration rates in river red gum woodlands.

10. Finalise outstanding papers

We have drafts of a number of papers at various stages of completion and further progress will be made on these in the coming months.

Methods

3. Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.

The following methodology has been broken down into field and lab components associated with carbon storage assessment, carbon sequestration assessment, aggregate stability assessment, assessment of river red gum water use, floristic surveys, bird surveys, and habitat condition assessment, with reference to relevant project objectives. All methods used are published standards, i.e. no new methods were developed specifically for this project.

Carbon storage

Vegetation biomass assessments were conducted at sites in spring 2012. For woody vegetation, this involved taking the diameter at 1.3 m above ground level (DBH) of all trees, the height of shrubs, the length and width of coarse woody debris. Tree diameters were related to total tree biomass according to published allometric equations for woodland and forest trees and shrubs (Snowdon et al. 2000). For herbaceous vegetation and litter, a modified version of BOTANAL (Tothill et al. 1978) was used, where dry weight biomass was estimated on a scale from 0 to 6 in 25 × 25 cm quadrats (n = 20, located at 4 m intervals around the perimeter of the 20 × 20 m herbaceous floristic vegetation quadrat) at each site, with each score related to an actual dry weight biomass of harvested calibration quadrats scored using the same system. Litter was scored in a similar fashion, with the number of 'handfuls' of litter estimated in the same 25 × 25 cm quadrats and related back to a set of calibration quadrats to determine the weight of litter. All values were expressed as tonnes of biomass on a per ha basis, with 50% of the total biomass estimated to be carbon (Snowdon et al. 2000). For soil carbon, 9 soil cores were taken in a 25 × 25 m quadrat encompassing the floristic quadrat, in four depth increments: 0–5 cm, 5–10 cm, 10–20 cm and 20–30 cm, as per (McKenzie et al. 2000, 2002). Soil samples were stored in dark boxes in a covered trailer parked in the shade during field trips (up to two weeks) then refrigerated on return to the lab prior to drying in 40°C ovens till dry. Air-dry and oven-dry moisture content were calculated in the lab by weighing pre- and post-drying. Soil samples were pushed through a 2 mm sieve then bulked (by weight) by depth at each site. Samples were then milled (0.5 mm) and analysed using the LECO combustion method, after treatment to remove carbonates, at the Environmental Analysis Laboratory at Southern Cross University in Lismore. More details can be found in Smith and Reid 2013.

Carbon sequestration

Nine sites in the lower Namoi were used to investigate the carbon sequestration potential of vegetation dominated by river red gums in floodplain and riparian contexts and in varying condition states (in terms of dieback intensity). The initial measurement period was spring 2008, with a follow up measurement taken in spring 2012. Rainfall conditions between time 1 and time 2 were average to above average, so sequestration rates documented in this study are likely to be at the higher end of what can be expected at these sites. Woody biomass growth only was the focus of this study, as estimation of soil carbon with only two data points is unreliable given the variability in soil carbon concentrations, particularly in riparian zones where floods can deposit or strip organic matter from the site. A literature review was also conducted to determine carbon sequestration rates in other relevant vegetation types for comparison. Methods were as above (see carbon storage section) for woody biomass estimation. The difference in biomass between time 1 and time 2 was calculated and divided by four years to give annual carbon sequestration rate. The literature review was used to inform the carbon neutral cotton farms project and until better data can be generated for cotton growing regions, has been included in the carbon calculator tool currently being built by Francois Visser and others.

Aggregate stability

Of the nine soil cores taken at each site, eight were chosen for aggregate stability analysis using wet sieving machines borrowed from ANU and CSIRO, Canberra. The 0–5 cm and 20–30 cm depths were of interest, and the eight samples chosen were based on having a large enough sample to cover requirements (particularly relevant to the 0–5 cm depth sample. Prior to bulking for carbon analysis, a 20 g sample passing a 10 mm sieve but retained on a 2 mm sieve, was placed on a nest of four sieves (2 mm, 1 mm, 0.5 mm and 0.25 mm mesh sizes from top to bottom) and sprayed gently three times with a handheld spray bottle. Samples were then placed on a machine that gently lifted samples up and down through a column of water for five minutes. Once finished, sieves were retrieved from the machine, separated and placed in an oven to dry for at least 2 hours (or until completely dried). Sieves, and the sample remaining on the sieve, were then weighed to determine the proportion of the original sample remaining on each sieve, and the proportion of sample passing the finest (0.25 mm) sieve). Calculations were then made to determine mean weight diameter of aggregates (MWD):

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \qquad \text{(Equation 1: Kemper and Rosenau 1986)}$$

Where MWD is the sum of products of (a) the mean diameter, X_i, of each size fraction and (b) the proportion of the total sample weight, W_i, occurring in the corresponding size fraction, where the summation is carried out over all n size fractions, including the one that passes through the finest sieve. Higher MWD denotes higher macroaggregate stability (Chaney and Swift 1984). More detail can be found in Smith et al. 2015.

River red gum water use
Oxygen and hydrogen isotope signatures of tree branchlets were compared with those of river, bore and soil water collected at two sites (Myall Vale and Old Narrabri Road) during a heatwave in January 2014 to determine water sources used by the trees. Nine trees were chosen representing three condition states (severely dieback affected, some dieback and healthy) at three distances from the Namoi River at each site. Samples of branchlets were taken from each tree pre-dawn and preserved in kerosene to prevent moisture loss prior to analysis. At the same time, samples were taken to determine pre-dawn water potential of the trees, and therefore moisture stress. Midday water potentials were also measured using a Scholander Pressure Chamber (Scholander 1964, 1965). Groundwater samples were taken from NSW Office of Water monitoring bores nearby each transect at the Myall Vale site. Three bores were also sampled at the Old Narrabri Road site, but unfortunately these were not aligned with the three transects. Water quality data (pH, EC, DO, etc.) was recorded at the time of sampling using a handheld water quality meter. River water samples were taken near the centre of the closest transect to the river. Soil water samples were taken at 1 m depth at a point near the centre of each transect. Samples were sent to the CSIRO at Waite, SA for extraction of water samples prior to isotope analysis at a lab in the United States of America. Unfortunately, three tree samples (one from Myall Vale, two from Old Narrabri Road) were lost by the freight company during transportation to the CSIRO lab and replicate samples were not available, resulting in an unbalanced experimental design.

Vegetation surveys
Floristic composition and biomass estimates were conducted at each site in spring 2012 and again during bird surveys in spring 2014. The identity and percentage cover of all herbaceous species was recorded in a 20 × 20 m permanently marked quadrat, while tall shrub and canopy cover was recorded in a 1 ha area with the dimensions of that area being dictated by the dimensions of the vegetation type being surveyed (e.g. riparian vegetation often required a long, narrow quadrat area to ensure there was no cross-over into adjacent vegetation communities).

Bird surveys
Two hectare, 20 minute surveys were conducted across all sites between September and December 2014. Surveys commenced in the north of the study region (near Emerald) and finished in the south of the region, near Darlington Point. Two surveys were conducted at each site, one by Dr Julian Reid, the other by Mr Stuart Green. Surveys were conducted between dawn and 10 am local time each day. Weather conditions (temperature, relative cloud cover and relative wind speed) were recorded during each survey and surveys were abandoned during windy conditions that would compromise the observers' ability to detect birds. All birds seen or heard in the 2 ha area were recorded and used in statistical analyses, and birds observed opportunistically outside the survey time and area were recorded separately.

Habitat condition
Habitat condition information was collected during bird surveys. Within each 2 ha bird survey area, habitat condition variables were assessed at 10 randomly chosen points to give an indication of the variability in habitat provision across the area. Habitat condition variables included: Canopy, tall shrub, low shrub, herbage, litter and bare soil cover, presence and relative amount of sheep/cattle dung and cut stumps, tree health/dieback class, dead standing trees, hollow trees, tree seedlings, mistletoe, distance to and type of water nearest the site (dam, river, creek, etc.), adjoining land use, other disturbances such as fire, digging or other human disturbances.

Results

4. Detail and discuss the results for each objective including the statistical analysis of results (note: for references, see relative published and draft papers).

Carbon storage
Parametric analysis of variance (AOV) in Statistix 8 (Analytical Software 2003) was used to examine differences in C contribution by woody vegetation, herbaceous vegetation, litter, CWD, dead standing

wood, roots, soil and total site C for each of the six vegetation types. Data were transformed to achieve normality; where normality of data could not be achieved using log or square-root transformations, rank-transformed data were used. Significant differences between vegetation types for each C component were determined using least significant difference (LSD). Spearman rank correlations were generated to highlight relationships between vegetation characteristics and C contribution in woody vegetation, herbaceous vegetation, litter, CWD, dead standing wood, and soil across all vegetation types. Spearman's correlations were used as data were not normally distributed. Differences were regarded as significant at $P \leq 0.05$.

River red gum

The largest quantity of C stored was found in river red gum vegetation (Table 1). River red gum sites generally consisted of large old-growth trees as reflected by large mean and maximum DBHOB values (Table 2). More than half of the C stored in river red gum sites came from woody vegetation (Fig. 1). Spearman correlations showed that the C stored in soil, litter, CWD and dead standing woody components was positively correlated with above-ground woody C (Table 3). Litter, CWD, dead standing tree and root biomass were also higher in river red gum sites than in other vegetation types. River red gum soils also had the highest TOC values and consistently had higher mean TOC down the profile to 30 cm depth ($F_{5,55} = 8.04$, $P < 0.001$) compared to other vegetation types (Fig. 2).

Coolibah

Coolibah sites had less than half the total C values of river red gum sites (Table 1). This was due to above-ground woody vegetation, on average, being less than half that of river red gum sites, though this difference was not significant (after rank transformation). Coolibah trees were generally about half the size of river red gums in DBHOB (Table 2). The woody vegetation and soil C components were similar and contributed approximately 40% each to total C in coolibah sites (Fig. 1). All other C-storing components made up approximately 20% of total C storage at coolibah sites; this value was similar across most of the wooded vegetation types.

Black box, myall and planted vegetation

In black box, myall and planted vegetation, the largest proportion of total site C was contained in the upper 30 cm of the soil (Fig. 1). Woody vegetation contributed approximately 30% of C to the overall store. Only minor amounts of C were found in herbaceous vegetation, litter, CWD, dead standing woody vegetation and plant roots, these components together averaging 7–18% across vegetation types. Myall, black box and planted sites had similar mean and maximum DBHOB values, which were considerably less than river red gum or coolibah (Table 2). However, the mean number of trees at each site was greatest in planted sites. Planted sites had the largest stores of C in litter of the six vegetation types, but variability in litter accumulation was high. Planted sites also had the highest herbaceous biomass of the wooded vegetation types, but this varied considerably depending on the density and age of the planting.

Grassland

Grassland vegetation contained the least C of all of the vegetation types (Table 1). This was due to the lack of woody vegetation at most grassland sites. Where trees were present in grassland sites, they tended to be relatively large with mean DBHOB similar to river red gum and coolibah sites (Table 2). Given the low woody biomass values in grassland sites, litter, CWD, dead standing trees, roots and TOC contributed very little to total C storage. Spearman's correlations showed that above-ground herbaceous C was negatively correlated with above-ground woody C (Table 3). Grasslands had, on average, the highest proportion of C in above-ground herbaceous biomass.

Table 1: Mean C (t C ha^{-1} ± 1 SEM) stored in ecosystem components by vegetation type. Different letters denote significantly different means between vegetation types for each ecosystem component in the rows ($P \leq 0.05$).

C component	Statistical significance	River red gum (n = 13)	Coolibah (n = 17)	Grassland (n = 17)	Myall (n = 6)	Black box (n = 4)	Planted (n = 4)
Total	$F_{5,55} = 26.7$ $P < 0.001$	215.9 ± 28.1a	100.8 ± 9.6b	40.1 ± 3.6d	69.7 ± 12.2bc	51.8 ± 7.1cd	63.4 ± 3.1bc
Woody	$F_{5,55} = 33.1$ $P < 0.001$	104.4 ± 20.0a	40.0 ± 6.5a	1.1 ± 0.6b	17.3 ± 2.2ab	15.4 ± 4.3ab	12.4 ± 3.2ab
Herbaceous	$F_{5,55} = 2.54$ $P = 0.039$	0.7 ± 0.1b	0.7 ± 0.1b	1.0 ± 0.1a	0.6 ± 0.1b	0.6 ± 0.1b	1.1 ± 0.3ab
Litter	$F_{5,55} = 7.65$ $P < 0.001$	1.6 ± 0.2a	1.1 ± 0.1ab	0.7 ± 0.1b	0.9 ± 0.3ab	0.7 ± 0.1ab	2.9 ± 0.7a
CWD	$F_{5,55} = 10.8$ $P < 0.001$	6.2 ± 2.1a	2.3 ± 0.9a	0.0 ± 0.0c	2.4 ± 0.6ab	0.4 ± 0.1bc	0 ± 0c
Dead standing	$F_{5,55} = 6.05$ $P < 0.001$	4.7 ± 1.5a	1.8 ± 0.6b	0.0 ± 0.0c	0.9 ± 0.4bc	0.9 ± 0.6bc	0.0 ± 0.0c
Roots	$F_{5,55} = 27.9$ $P < 0.001$	26.5 ± 0.5a	10.3 ± 1.6b	0.8 ± 0.2d	4.6 ± 0.5c	4.1 ± 1.1c	3.6 ± 0.7c
TOC (0–30 cm)	$F_{5,55} = 8.04$ $P < 0.001$	71.7 ± 4.4a	44.7 ± 3.8b	36.4 ± 3.7b	43.1 ± 9.6b	29.7 ± 2.2b	43.3 ± 7.3b

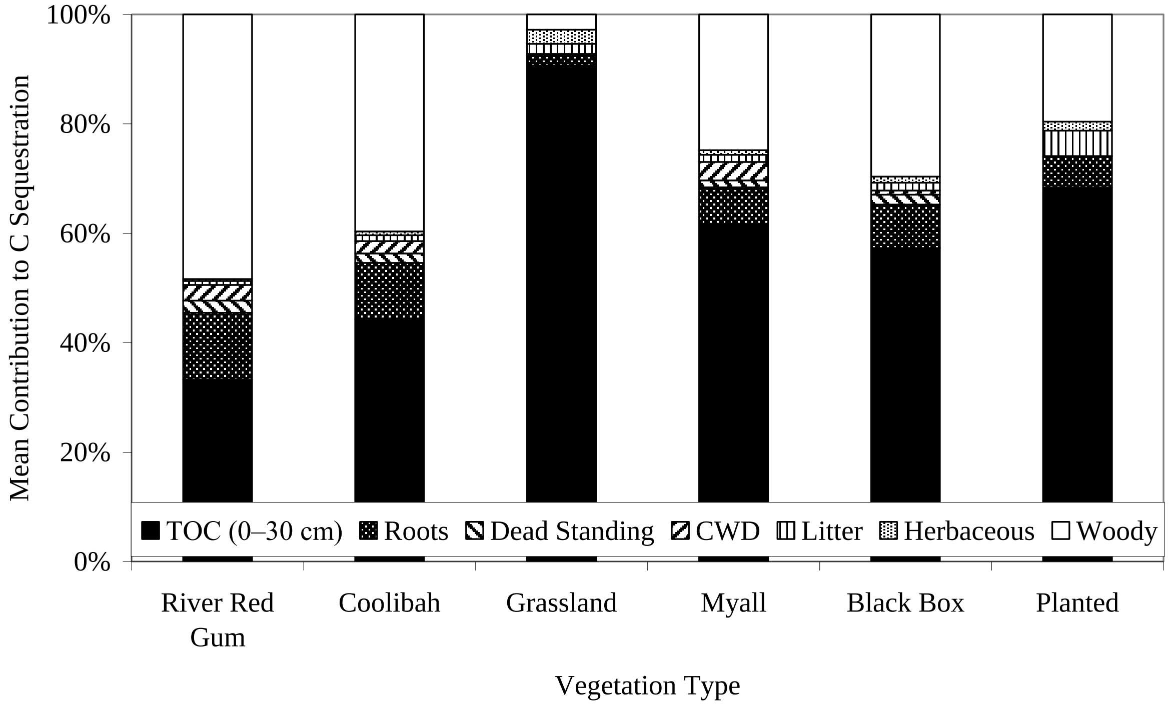


Figure 1: Proportion of mean total site C contributed by each ecosystem component.

Table 2: Mean and maximum DBHOB of the dominant species and mean number of trees in 1 ha at sites by vegetation type. Note: trees of all species included in grassland and planted sites. Different letters denote significantly different means in the rows ($P \leq 0.05$).

Tree measurements	Statistical significance	River red gum (n = 13)	Coolibah (n = 17)	Grassland (n = 7)*	Myall (n = 6)	Black box (n = 4)	Planted (n = 4)
Mean DBHOB (cm)	$F_{5,45} = 6.52$ $P < 0.001$	68.5 ± 10.9a	28.8 ± 5.1b	36.1 ± 6.6ab	17.8 ± 5.2b	19.8 ± 3.8b	11.8 ± 1.9b
Max DBHOB (cm)	$F_{5,45} = 12.2$ $P < 0.001$	217.0a	104.0b	74.0b	61.0b	67.0b	29.0b
Mean number of trees at sites (per ha)	$F_{5,45} = 12.6$ $P < 0.001$	99.5 ± 37.3b	318.1 ± 149.3ab	1.2 ± 1.0c	295.7 ± 163.8ab	116.0 ± 49.6ab	508.0 ± 46.0a

* Ten grassland sites were excluded from analyses as there were no trees present.

Table 3: Spearman correlation matrix for C contribution in different ecosystem components (n = 61). Note: root C was based on above-ground woody vegetation.

	Woody	Herbaceous	Litter	CWD	Dead standing	Root	$\text{TOC}_{0–30}$
Herbaceous	–0.26*						*$P \leq 0.05$
Litter	0.55**	–0.23					**$P \leq 0.01$
CWD	0.80**	–0.39**	0.38**				
Dead standing	0.66**	–0.39**	0.36**	0.69**			
Root	0.98**	–0.17	0.55**	0.79**	0.64**		
$\text{TOC}_{0–30}$	0.46**	–0.03	0.39**	0.32*	0.18	0.44**	
Total	0.89**	–0.20	0.59**	0.72**	0.57**	0.88**	0.77**

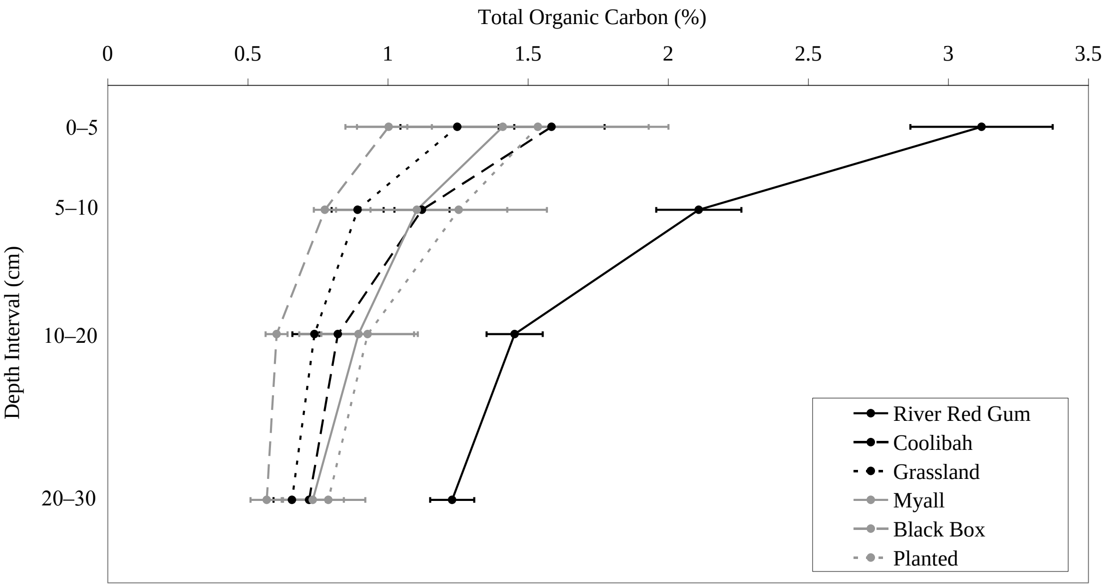


Figure 2: Mean TOC distribution (± 1 SEM) by vegetation type. River red gum sites, on average, consistently had significantly higher TOC concentrations down the soil profile when compared to other vegetation types ($P < 0.05$).

Four major results of our study are emphasised here. First, woody vegetation was a strong determinant of total site C storage. Woody biomass was positively correlated with litter, CWD, dead standing tree and TOC. Even when hollow formation was accounted for, sites with multiple old-growth trees stored more carbon than sites with fewer or no old-growth trees. This result is consistent with numerous studies from around the world (e.g. Harmon *et al.* 1990; Jandl *et al.* 2007; Luyssaert *et al.* 2008; Schultze *et al.* 2000; Wilson *et al.* 2008; Young *et al.* 2005), and underscores the value of woody vegetation in C storage and sequestration.

Second, we showed that C is partitioned differently within distinct ecosystems. The relative importance of the various C-storing components depends on the abundance of woody vegetation. In ecosystems with lots of woody biomass, C was stored equally between the woody biomass and associated components (CWD, litter, dead standing trees), and the soil. However, in ecosystems with less woody biomass, TOC was the dominant C store. In grassland sites, >90% of total site C was stored in the top 30 cm of the soil profile. In general, larger tree basal area resulted in lower herbaceous vegetation biomass. At sites with abundant woody biomass, herbaceous vegetation therefore contributed little to total site C, as found by Jackson and Ash (1998), Scanlan and Burrows (1990), Scholes (2003), and Scholes and Archer (1997). However, in open woodland and grassland ecosystems, herbaceous vegetation may provide a significant proportion of C inputs to the soil.

Third, within C-storing components, ecosystems differed in the way in which C was partitioned. For example, the high concentration of TOC in the surface 0–5 cm of the soil profile in river red gum and perhaps coolibah sites indicated that the soils received greater C inputs at the surface than from deeper in the soil profile. This result is consistent with data presented by Jobbágy and Jackson (2000), who reported that the majority of soil C in forested ecosystems is found in the surface soil, more so than in grasslands. This is due to the way different vegetation types partition biomass. In grasslands, a high proportion of annual production occurs below ground and this is the greatest input of C to the soil, whereas in wooded ecosystems the dominant C input from the vegetation to the soil is through litter deposition (Jobbágy and Jackson 2000).

Finally, our study confirmed that C is distributed unevenly on floodplains, being concentrated in riparian areas where nutrients are abundant, floods are frequent and access to water is not a limiting factor. This is reflected in the dimensions (height and DBH) of the dominant species, i.e. river red gum and coolibah trees achieve greater dimensions than black box and myall. The turnover times for litter and woody debris also plays a role in C accumulation in each of the vegetation communities. Woody debris and litter derived from eucalypts has a higher C:N ratio, and therefore has a longer residence time than litter derived from grasses (Snowdon et al. 2005). As such, some vegetation types are disproportionately important for C storage. This result is consistent with studies elsewhere that show greater net primary productivity (NPP) in riparian areas compared with other parts of the floodplain (Naiman *et al.* 2005). While each of the vegetation types surveyed here has different values in terms of biodiversity conservation, forage production and other ecosystem services, given the value of riparian areas in storing large amounts of C, appropriate management and protection of these areas should be a priority in climate change mitigation strategies.

We have demonstrated that woodlands, such as those occurring on cotton farms, represent a significant carbon store, and a small, but significant and often overlooked C sink (Burrows et al. 2002). Burrows et al. (2002) estimated the mean net above-ground annual C increment for 57 savanna woodland sites across Queensland (including the Darling Downs region) was 0.53 t C ha (0.53 × 3.667 = 1.94 tonnes CO_2(e)) each year. Grace (2008) calculated approximately 446.5 tonnes CO_2(e) is emitted each year on an average mixed farming enterprise (100 ha grazed pastures, 100 ha of dryland cropping and 200 ha of irrigated crops such as cotton) in the Darling Downs region of Queensland. Approximately 230 ha of woodland vegetation would be required to offset C emissions and achieve a C neutral enterprise on Grace’s case study farm. Approximately 40% of the average Australian cotton farm is native vegetation (Inovac Consulting 2012). Using the data of Burrows et al. (2002) and Grace (2008), the average Australian cotton farm should be carbon neutral, and may be accumulating a small amount of C.

This study and many others (e.g. Harmon *et al.* 1990; Jandl *et al.* 2007; Luyssaert *et al.* 2008; Schultze *et al.* 2000) illustrate the importance of existing native vegetation, especially old-growth woodlands and forests, in storing large amounts of C. There is a case for the development of incentives for landholders in the form of C credits for protection and appropriate management of these stores in order to avoid large amounts of C entering the atmosphere. Currently, landholders that protect areas of remnant native vegetation on their land are unable to access C credits under the rules of the Kyoto Protocol. In Australia, the Carbon Farming Initiative (http://www.climatechange.gov.au/reducing-carbon/carbon-farming-initiative) clearly states that ‘the establishment of a conservation covenant in perpetuity over native vegetation’ is not an eligible C abatement activity and does not attract C credits. However, ‘the protection of native forest from clearing where the landholder received consent to clear before 1 July 2010’ is an eligibly abatement activity under strict conditions. The data presented here show that landholders are providing a valuable service to the wider community by maintaining remnant native vegetation on their land. If this effort is not recognised and rewarded, market and other forces could drive landholders to transform these areas for farming and crop production at times when land-use controls over vegetation clearance are relaxed (Norton and Reid 2013).

Carbon sequestration

Literature review

A literature review determined net primary productivity (NPP) of vegetation types commonly encountered on ‘Redbank’ (Table 4). The age of the vegetation (e.g. young or old tree regeneration, mature or old growth trees), density of trees (e.g. scattered trees, woodland or forest) and management history (e.g. thinning, grazing or burning) need to be taken into account when selecting appropriate vegetation types for comparison. We assumed C sequestration was equal to half of the NPP (Dwyer et al. 2009; Gifford 2000; Horner et al 2010). Where direct measurements of NPP could not be found for some vegetation communities, but the age of the vegetation was known, C-storage was divided by the age of the vegetation to give average NPP over time.

Table 4: Areas of native vegetation on 'Redbank,' their management and potential C-sequestration rate based on net primary productivity (NPP).

Vegetation type	Farm area (ha)	Management/land use/structure	C-seq. rate (t C ha^{-1} yr^{-1})	Total C seq. (t yr^{-1})	Total C seq. (t yr^{-1} CO2(e)
River red gum riparian forest	153.5	Old-growth, mature and regenerating trees, some tree thinning	2.07[1]	317.75	1165
Coolibah woodland	6.6	Old-growth, mature and regenerating trees	0.50[2]	3.3	12.1
Regenerating brigalow	114.5	Pockets of dense regeneration	0.65[3]	74.43	272.9
Mature and regenerating poplar box and brigalow	332	Multiple-stemmed poplar box with mature, open brigalow	0.60[4]	199.2	730.5
Tropical pasture	53	Bambatsi panic, Rhodes grass	0.40[5]	21.2	77.7
Native grasslands	179.5	Mix of perennial grasses	0.27[6]	48.47	177.7
Total Farm Veg	839.1			664.35	2436.2
Average ha^{-1}				0.791	2.90

1. Robertson et al. 2001; 2. Burrows et al. 2002; 3. Chandler et al. 2007; 4. Moore et al. 2007;
5. Lodge and Johnson 2010; 6. Garnaut 2008.

Namoi river red gums study

Data were analysed using the 'lme' function within the 'nlme' package (Pinheiro et al. 2014) in R (R Core Team 2015). Two separate analyses were conducted, one for each of the two dependent variables, C sequestration and tree growth rate (i.e. diameter increment). The potential explanatory variables initially considered as fixed effects in both analyses were initial DBH (i.e. the DBH of trees in 2008), density (i.e. the number of stems per ha at each site), position (i.e. floodplain or riparian) and dieback (i.e. the average degree of canopy dieback at each site). We also included the square of density, dieback and DBH to allow for non-linearity in response. Site was included as a random effect to avoid pseudo-replication and ensure that the correct degrees of freedom value were used for the site-level factors, dieback, position and density. Initial analysis indicated that dieback and position were confounded, so DBH, density and dieback were included as explanatory variables, as dieback was considered more likely to directly influence growth and C sequestration due to the ability of river red gums to access groundwater when growing in floodplain locations. We also substituted position for dieback in models, to test whether position explained either response variable as well as dieback.

Residual plots indicated heteroscedasticity (non-constant variance), so the variance structure of the data was modelled first using the 'weights' option in the 'lme' function, with the best variance structure determined by comparing AIC and standardised residual plots (Zuur et al. 2009). Log and square-root transformations were considered where needed to improve residual plots. For both C sequestration and growth rates, variance structure was best modelled as a power function of fitted values, after a square-root transformation of the original values.

Once the best variance structure and transformations were determined, the models were step-wise simplified based on AIC. This involved dropping the term from the model that most improved (lowered) AIC sequentially until a minimum AIC was achieved. To enable valid AIC comparison, fitting was based on maximising log-likelihood instead of the default, restricted log-likelihood (Zuur et al. 2009, Pinheiro et al. 2014). P-values for terms remaining in the final models were obtained based on marginal *t*-tests using the model 'summary' function.

Riparian sites were generally denser (had more stems per ha), experienced less dieback, and consisted of smaller trees or had a range of tree sizes compared to floodplain sites. Floodplain sites were predominately dominated by sparse, large, dieback-affected trees (Table 5). One floodplain site (KIL2) was very dense and occurred on a prior stream of the Namoi River. Another site, MOL2, was classified as riparian, but was located on a high river bank that would have experienced low flood frequencies. When cumulative C sequestration was calculated on a site-by-site basis and sites ordered on this basis (Table 4), healthy sites with little or no dieback in riparian positions had the highest site-level biomass production and C sequestration rates. Average annual carbon sequestration rate was 2.54 t ha^{-1} yr^{-1}.

Table 5: C sequestration by river red gums across the lower Namoi Catchment ordered by highest to lowest C sequestration

Site number	Site name	Dieback class	Landscape position	Tree density (stems ha^{-1})	2008 DBH (cm, mean ± 1 SE)	Site-level C sequestration (t ha^{-1} yr^{-1})
1	SR5	Healthy	Riparian	120	40.9 ± 5.5	8.96
2	RED1	Healthy	Riparian	190	53.7 ± 7.0	5.54
3	WAL14	Healthy	Riparian	216	30.9 ± 5.2	5.02
6	MOL2	Intermediate	Riparian	18	141.6 ± 6.7	1.55
4	KIL2	Intermediate	Floodplain	464	28.3 ± 2.9	0.65
5	SR4	Intermediate	Floodplain	15	88.3 ± 14.3	0.47
9	GA1	Poor	Floodplain	22	132.2 ± 11.3	0.40
8	SR9	Poor	Floodplain	48	39.6 ± 9.4	0.13
7	SR8	Poor	Floodplain	8	45.1 ± 24.9	0.11
						Average = 2.54

Within sites, C sequestration rates generally increased with tree size (Figure 3). The final model explaining C sequestration rates included initial DBH, density and dieback (Table 6), and indicated that, within sites, C sequestration rates increased with tree size up to a point and then plateaued (Figure 3), while denser sites and sites with higher levels of dieback had lower C sequestration rates. When substituted for dieback, position was also significant (P = 0.0131), with C sequestration rates considerably lower in floodplain than riparian locations. Site was not significant as a random effect in explaining C sequestration rate, indicating that the fixed effects (initial DBH, density and position or dieback) accounted for the majority of the variation in C sequestration rates among sites.

River red gums had high growth rates during this study. Growth rates were as high as 6 cm yr^{-1} at one site (SR5) that consisted of widely-spaced, healthy trees in a riparian position (Figure 3). Most trees had growth rates <3 cm yr^{-1}. Tree growth rate declined significantly with tree size (DBH), density and greater levels of dieback (Figure 3, Table 6). When substituted for dieback, position was also significant (P = 0.0145), with growth rates lower in floodplain than riparian locations. Site was not significant as a random effect in explaining growth, so the fixed effects (initial DBH, density and position or dieback) accounted for the majority of the variation in growth rates among sites.

Table 6: Final models to explain growth rates and C sequestration in river red gum trees. The terms retained in the final model are indicated, together with estimated coefficient value, standard errors of these values, relevant degrees of freedom, *t*-value, and P-value for each term. Note that in some cases, non-significant (p > 0.05) terms were retained because dropping them from the model increased model AIC.

	Value	Std. Error	DF	*t*-value	P-value
Final Model for Growth					
Initial DBH	–0.00567	0.00143	78	–3.97508	0.00016
Density	–0.00248	0.00054	6	–4.59628	0.00371
Dieback	–0.33055	0.09773	6	–3.38233	0.01482
Final Model for C Sequestration					
Initial DBH	0.085	0.017	77	4.95	<0.0001
Density	–0.04	0.014	5	–2.79	0.038
Dieback	–3.54	0.81	5	–4.38	0.007
Initial DBH^2	–0.00032	0.00013	77	–2.367	0.020
Density: dieback	0.014	0.0065	5	2.21	0.078

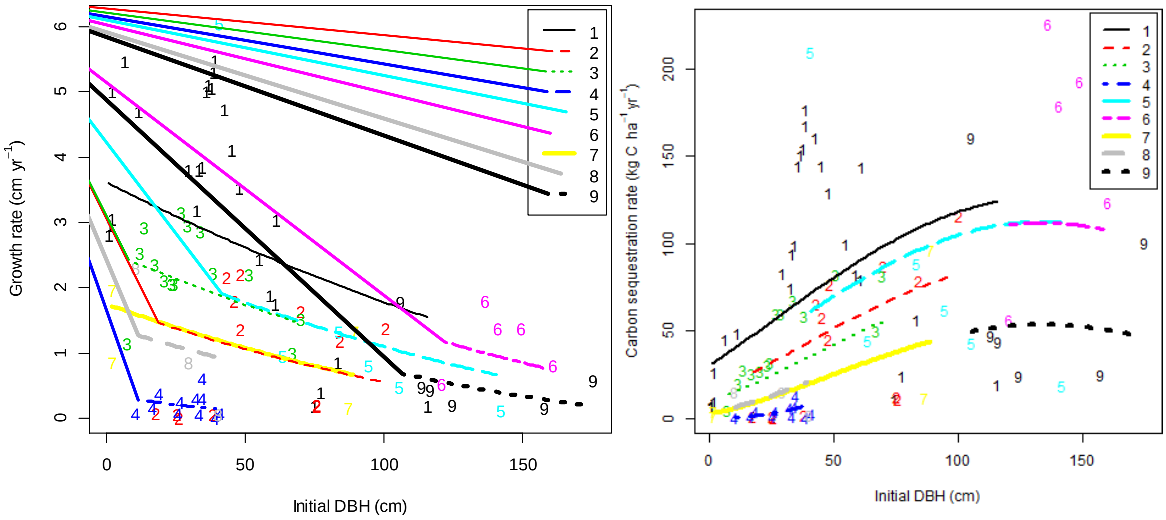


Figure 3: (a) River red gum growth rates in relation to initial DBH at nine sites. Each point/numeral represents original data for one tree, with the numeral representing the site number. Each line indicates the final model predictions for one of the nine sites. (b) C sequestration rates in the Namoi catchment, 2008–12. Each point/numeral represents original data for one tree, with the numeral representing the site number. Each line indicates the model predictions for one of the nine sites (first model, lowest AIC).

Using the model relating growth rate to tree size, stem density and site position, we modelled cumulative growth through time to allow prediction of tree age based on size (Figure 4). The model indicated that trees located in riparian positions where trees were sparse showed maximum growth in the first 20–30 years with a slow decline in growth rate thereafter. Trees located in dense floodplain sites experienced very low but sustained growth over the first 150 years. Trees located in sparse floodplain and dense riparian sites showed intermediate growth rates through time, with trees at dense riparian sites having higher growth rates than sparse floodplain trees.

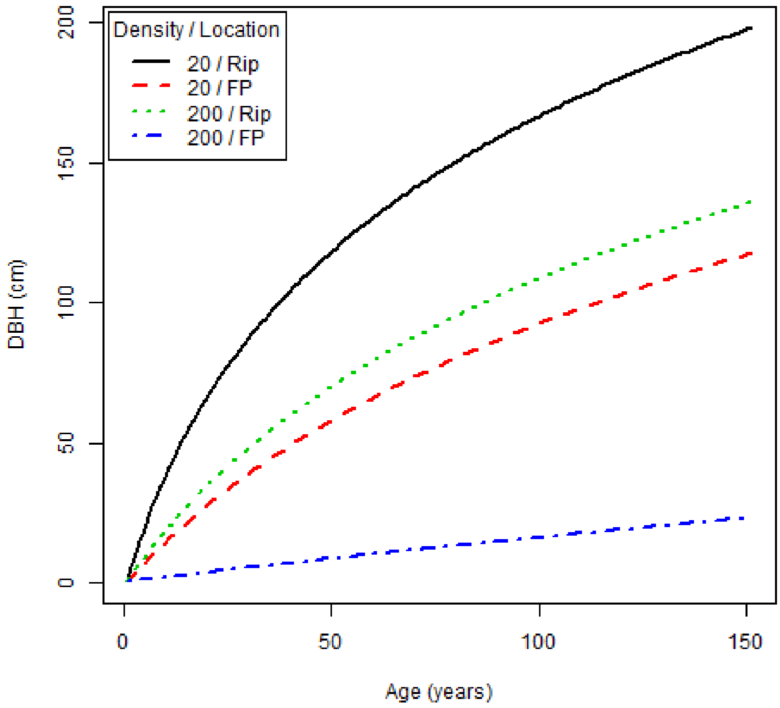


Figure 4: Estimated tree age based on DBH, tree density and position in the landscape. Note: age may be underestimated as maximum growth rates rather than average growth rates were used in this model.

Knowledge of growth, biomass accumulation and C sequestration rates, and of the influence of various environmental factors in determining C accumulation in semi-arid riparian ecosystems worldwide is vital to understanding C dynamics and budgets. This study highlights the potential importance of old-growth riparian ecosystems in sequestering large amounts of C during periods of average to above-average rainfall associated with La Niña conditions in inland eastern Australia (latitude 30°S). Under El Niño conditions, growth and C sequestration rates are likely to be lower, as trees go into 'survival mode.'

Our study showed growth rates decreased with tree age, but were on average, higher than most published studies of eucalypt species in Australia. Published growth rates for river red gums vary considerably, from less than 2 mm yr^{-1} (Colloff 2014) to more than 2.5 cm yr^{-1} in remnant and regenerating forests in southern and central NSW (Jacobs 1955; Colloff 2014; Taylor et al. 2014). Differences in published growth rates are attributable to stand density, environmental conditions (flood frequency and duration, insect attack, etc.) and tree size. In several cases, published studies indicate that larger trees exhibit greater diameter increment (Colloff 2014). Taylor et al. (2014) found growth rates >2 cm yr^{-1} in remnant woodlands in central NSW, but these were thought to be erroneous values and were excluded from analysis. Growth rates comparable to those recorded in this study for healthy young trees in remnant stands (i.e. up to 6 cm yr^{-1}) are unprecedented. However, growth rates of this magnitude have been recorded in tropical plantations of river red gums in Asia (Doran and Wongkaew 2008).

While we found that diameter increment decreased with age, we showed that biomass accumulation rates may increase with tree size. This result is consistent with recent studies (Bowman et al. 2013; Matchinari et al. 2015; Stephenson et al. 2014; Taylor et al. 2014) and also aligns with studies that show the potential for significant C sequestration in relatively undisturbed old-growth forests worldwide, and the value of mature forest as C sinks (Baldocchi 2008; Carey et al. 2001; Luyssaert et al. 2008; Paw et al. 2004; Pregitzer et al. 2004; Zhou et al. 2006). Luyssaert et al. (2008) showed that an average 200-year-old temperate or boreal forest could sequester, on average, 2.4 ± 0.8 t ha^{-1} yr^{-1} of C. Our site-level C sequestration rates were comparable, on average (2.54 t ha^{-1} yr^{-1} of C).

A crucial part of the equation that is missing from many studies of C sequestration in old-growth trees, including this study, relates to hollow development and wood decay rates. Many studies use allometric equations that do not represent the full range of tree sizes encountered during studies. This is particularly true of very large trees (i.e. >1 m DBH), due to the difficulty in weighing such trees to develop allometric equations (Sillett et al. 2015). In Australia, there is only a handful of allometric equations developed using trees with DBH > 100 cm (Keith et al. 2000) and none of those equations were deemed suitable for this study. While we acknowledge our biomass accumulation and C sequestration measurements may be overestimates, we hypothesize that the rate of increase in woody biomass would still out-pace decay and hollow development in river red gums over the timeframe of this study. Laboratory studies indicate that coarse woody debris of river red gum has a lifetime of 375 years (Mackensen et al. 2003). River red gums have moderate wood density, are relatively termite-resistant (Boland et al. 2006) and termite activity is low in these ecosystems due to the shrink–swell nature of the soil (Moore et al. 1967) and frequency of flooding.

Aggregate stability

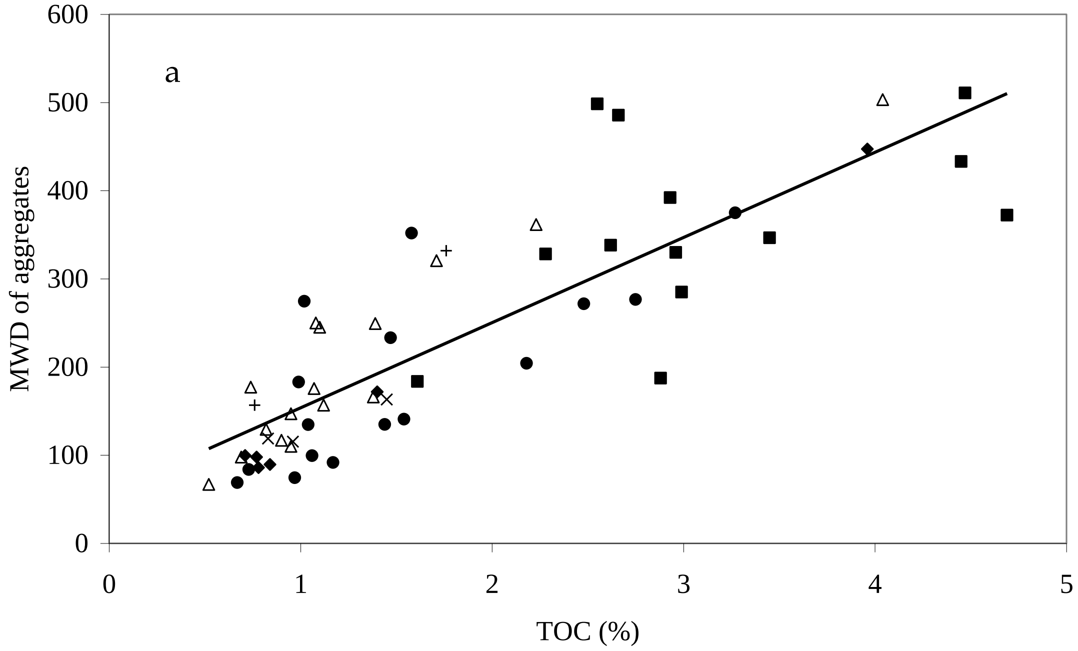
One-way Analysis of Variance (ANOVA) and Tukey's HSD pairwise comparisons were used to investigate differences in surface and subsoil characteristics between vegetation types using Statistix 8 (Analytical Software 2003). Data were transformed as necessary, the assumptions of tests were satisfied, and differences were reported as significant where $P \leq 0.05$. All reported soil and vegetation values are untransformed unless specified. The same approach was used to investigate differences in vegetation characteristics (litter biomass and cover, herbaceous vegetation biomass and cover, and canopy cover) between vegetation types.

Spearman rank correlations were generated for all pairs of physico-chemical variables for surface ($n = 56$) and subsoil ($n = 56$) samples separately in Statistix 8. Differences were reported as significant where $P \leq 0.05$. Spearman rank correlations guided the selection of appropriate variables for subsequent multiple stepwise regression. The Schwartz (1978) Bayesian Information Criterion (BIC) in R 3.0.2 (R Core Team 2013) was used to find the most parsimonious regression model to explain surface and subsurface MWD of aggregates and ASWAT using the backward selection procedure. The starting variables for the multiple stepwise regression differed for surface and subsoils. Variables included in the initial models to explain MWD of aggregates were TOC and clay for surface soils, and TOC and EK for subsoils. Variables included in the initial models to explain ASWAT scores were Ca and ESP for surface soils, and Na and silt for subsoils. These variables were chosen to minimise collinearity (illustrated by Spearman rank correlations matrices), while maintaining as much explanatory power as possible. General linear models were used to examine MWD, while generalised linear models (GLMs) were used to examine ASWAT due to the ordinal nature of the ASWAT measurement.

Correlations between variables retained in the final models predicting MWD in surface and subsoils and vegetation attributes were undertaken tested to determine associations between vegetation-related variables (herbaceous biomass and cover, canopy cover, litter biomass and litter cover), and the predictors of surface and subsurface MWD to determine the contribution of vegetation characteristics to soil stability. Due to frequent non-normality of variables, Spearman's rank correlations were used. Differences were reported as significant where $P \leq 0.05$.

Significant differences between vegetation types were demonstrated for many surface soil characteristics, including MWD, ESP, TC, TOC, N and C:N ($P \leq 0.001$), pH, Ca, Mg, ECEC, EK and silt ($P \leq 0.01$), and ASWAT, Na, Ca:Mg, ECa, and EMg ($P \leq 0.05$). No significant differences between vegetation types were found for EC, K, clay or sand in the surface soil. Analysis of subsoil characteristics showed significant differences between vegetation types in MWD, pH, EC, Ca, Na, Ca:Mg, ECa, EMg, ESP, TC, TOC, N and C:N ($P \leq 0.001$), for ASWAT and silt ($P \leq 0.01$), and for EK ($P \leq 0.05$). No significant differences between vegetation types were found for K, ECEC, clay or sand in the subsoil (see Smith et al. 2015 for details).

MWD by vegetation type was approximately half in the subsurface samples compared to the surface samples. In both the surface and subsoil samples, aggregate stability (MWD) was significantly positively correlated with TC, TOC, silt, ECa, and N. MWD in the surface soil was negatively correlated with clay, Na, K, ESP and pH. In the subsoil, MWD was negatively correlated with clay, Na, ECEC, ESP, EK, pH and EC (see Smith et al. 2015 for details). The stepwise regressions for both surface and subsoil samples included only TOC to explain MWD of soil aggregates. Linear regression analysis showed the relationship between MWD and TOC was highly significant in both cases ($P < 0.001$), though the relationship between MWD and TOC in the surface soil was stronger ($R^2 = 0.70$; Figure 5a) than in the subsoil ($R^2 = 0.51$; Figure 5b).



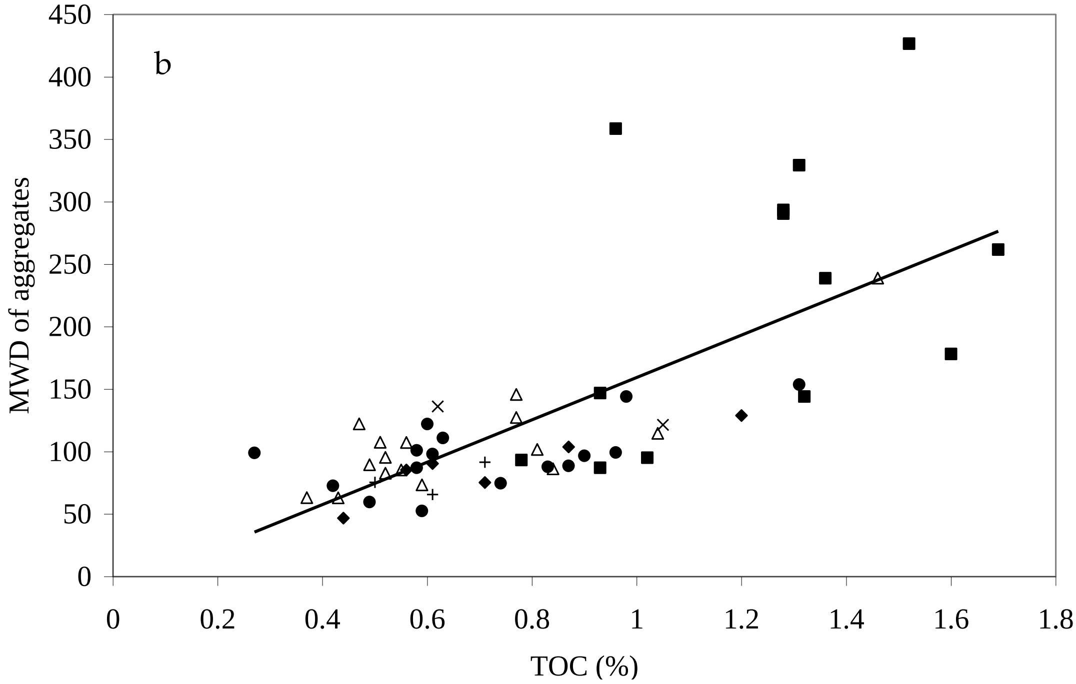
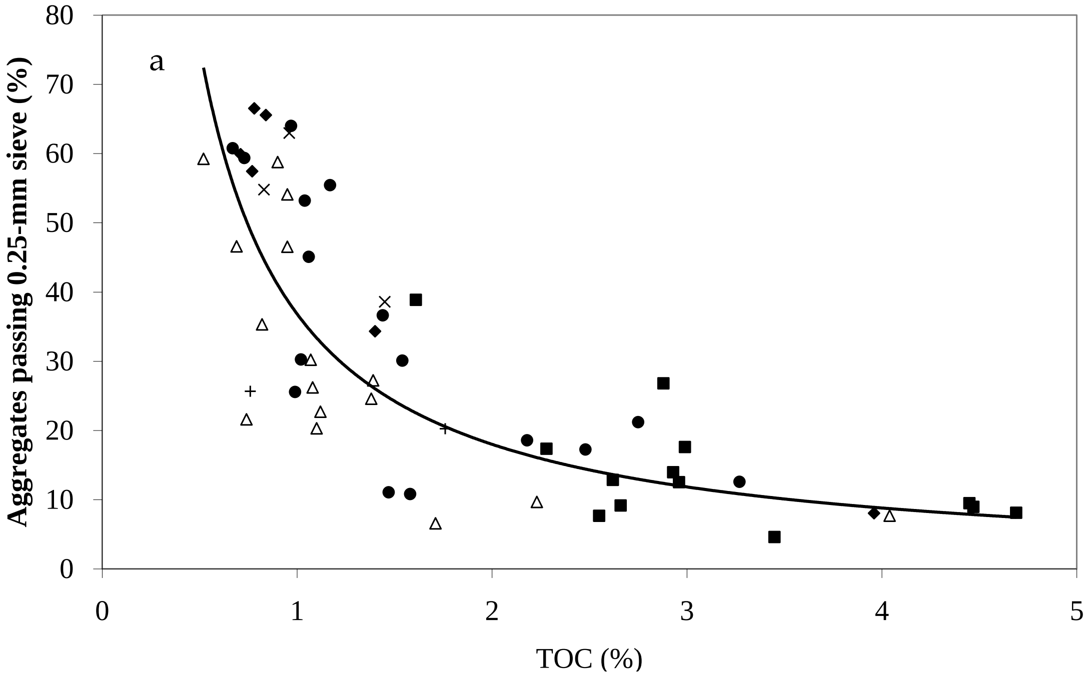


Figure 5: Linear regression between MWD and TOC (n = 56) in (a) surface soil samples (MWD ~ 98.38*TOC + 60.29, Adjusted $R^2 = 0.70$, $P < 0.001$) and (b) subsurface soil samples (MWD ~ 169.30*TOC – 10.96, Adjusted $R^2 = 0.51$, $P < 0.001$). ■ = river red gum, ● = coolibah, △ = grassland, ◆ = myall, × = black box, + = planted.

In the surface soil, 11 sites had MWD >350 and 10 of these sites had more than 2% TOC, with the majority having ≥3% TOC (Figure 6a). Of the 11 sites that had MWD >350 in the surface soil, six of these were river red gum-dominated sites. Ten sites had less than 10% of aggregates passing the 0.25-mm sieve, and all but one of these sites had TOC > 2% (Figure 6a). A power function ($y = 36.835x^{-1.0334}$) generated to explain the relationship between TOC and the percentage of aggregates passing the 0.25-mm sieve in the surface soil indicated that > 3.5% TOC was required to keep 90% of aggregates from passing the 0.25-mm sieve ($R^2 = 0.62$). In the subsoil, only two sites had MWD > 350, both of these being river red gum sites (Figure 6b). Three sites had less than 10% of aggregates passing the 0.25-mm sieve, and all three were river red gum sites (Figure 6b). A linear relationship generated to explain the relationship between TOC and the percentage of subsurface aggregates passing the 0.25-mm sieve indicated that approximately 1.5% TOC was required to keep 90% of aggregates from passing the 0.25-mm sieve ($R^2 = 0.53$).



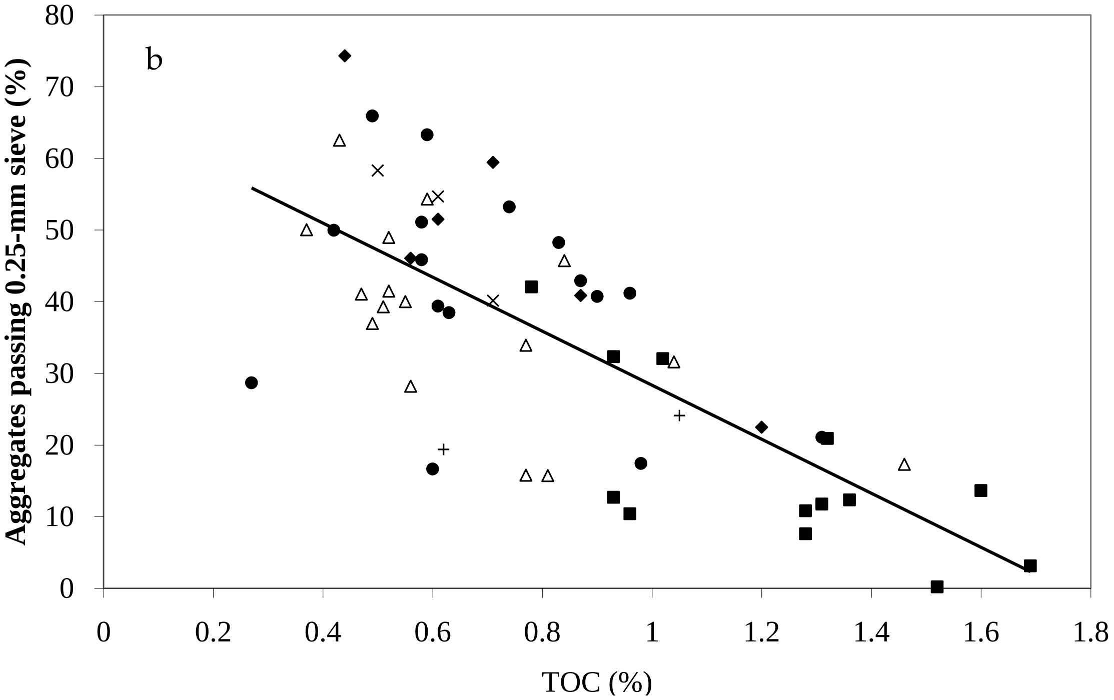


Figure 6: Relationship between the proportion of sample passing the finest sieve (0.25-mm mesh) and TOC (n = 56) for (a) surface ($R^2 = 0.68$) and (b) subsurface soil samples ($R^2 = 0.53$). ■ = river red gum, ● = coolibah, △ = grassland, ◆ = myall, × = black box, + = planted.

ASWAT scores in surface soils were correlated with clay, ESP and Na (positive), and TC, TOC, C:N, silt, Ca, Ca:Mg, ECa, EC and N (negative; Table 3). In subsoils, ASWAT was positively correlated with clay, Mg, Na, K, ECEC, ESP, pH and EC, and negatively correlated with TC, TOC, silt, Ca:Mg, ECa and N (Table 4). Stepwise regression and GLMs showed that ESP ($P < 0.001$) and Ca ($P = 0.005$) explained surface ASWAT scores (Table 7). For subsoils, only Na was required to explain high ASWAT scores ($P < 0.001$).

Table 7: Analysis of deviance table for final models explaining ASWAT scores in 56 surface (0–5 cm) and 56 subsurface (20–30 cm) soil samples.

Variables	d.f.	Deviance explained	d.f.	Residual deviance	Pr (χ^2)
Surface ASWAT					
ESP	1	23.74	53	91.54	< 0.001
Calcium	1	7.77	52	83.77	0.005
Subsurface ASWAT					
Na^+	1	58.08	54	112.86	< 0.001

Litter biomass and cover, herbaceous biomass and cover, and canopy cover were significantly different between vegetation types ($P < 0.05$; Table 8). River red gum and planted sites had significantly higher litter biomass and cover than other vegetation types. River red gum and grassland sites had significantly higher herbaceous plant cover than other vegetation types while coolibah and myall sites had significantly less than other vegetation types. All vegetation types had similar mean canopy cover except grasslands, which had significantly less canopy cover than other vegetation types.

Table 8: Mean litter, herbaceous vegetation, canopy and total understorey cover (%), and litter and herbaceous vegetation biomass (tonnes DM/ha) for each vegetation type. Letters indicate significant differences (Tukey $P \leq 0.05$).

	Significance	River red gum (n = 13)	Coolibah (n = 16)	Grassland (n = 16)	Myall (n = 6)	Black box (n = 3)	Planted (n = 2)
Litter biomass[1] (t DM/ha)	$F = 6.31$, $P < 0.001$	3.3ab	2.2b	1.5c	2.4b	1.4b	6.0a
Litter cover[1] (%)	$F = 6.36$, $P < 0.001$	48.3a	31.3ab	20.5b	27.7ab	12.567b	73.5a
Herbaceous biomass (t DM/ha)	$F = 2.85$, $P = 0.024$	1.5a	1.4a	2.2a	1.1a	1.2a	1.9a
Herbaceous cover (%)	$F = 7.00$, $P < 0.001$	43.4a	22.3c	38.2ab	19.5c	22.0abc	30.9abc
Canopy cover[1] (%)	$F = 7.67$, $P < 0.001$	22.4a	23.9a	1.2b	17.5a	21.0ab	20.0ab
Total understorey cover	$F = 8.78$, $P < 0.001$	84.4a	55.9ab	55.2ab	46.81b	37.5b	90.8a

[1] log-transformed: log(x+1) prior to ANOVA

Data from all sites showed that surface soil TOC was positively correlated with litter biomass, litter cover, herbaceous plant cover and total understorey cover (Table 9). Litter variables were positively correlated with canopy cover while both herbaceous plant variables were negatively correlated with canopy cover. No significant correlations were found between subsurface TOC and any vegetation variables.

Table 9: Spearman correlations between selected vegetation variables and surface and subsurface TOC (n = 56).

	Surface TOC	Subsurface TOC	Litter biomass	Litter cover	Plant biomass	Plant cover	Canopy cover
Subsurface TOC	0.25						
Litter biomass	0.44***	0.18					
Litter cover	0.55***	0.24	0.87***				
Plant biomass	–0.02	–0.20	–0.31*	–0.30*			
Plant cover	0.49***	–0.03	–0.05	0.06	0.61***		
Canopy cover	0.22	0.01	0.48***	–0.44***	–0.38**	–0.27	
Total understorey cover	0.72***	0.21	0.70***	0.84***	0.03	0.53***	0.31*

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

Discussion

The results presented in this paper indicate that 3% TOC was required to stabilise surface soil macroaggregates in vertosols (MWD > 350), and 3.5% TOC was required to retain 90% of macroaggregates within the nest of sieves. Macroaggregate stability in both the surface (0–5 cm) and subsurface (20–30 cm) soils increased with sufficient TOC. The relationship between MWD of aggregates and TOC in the surface soil was stronger where TOC regularly exceeded 2%. The results of this study are contrary to the proposition that vertosol macroaggregate stability cannot be increased by organic matter input (Charman and Roper 2000; Coughlan and Loch 1984; Coughlan et al. 1987; Dalal and Bridge 1996; Prebble 1987; Reichert and Norton 1994; Smith 1984).

Most prior studies of aggregate stability in vertosols were conducted on samples taken from cropping or pasture situations rather than natural woodland and forest systems where C concentrations regularly exceed 2% (Figure 1). Samples from paired ‘virgin’ soils used for comparison of soil conditions in previous studies were predominantly taken from grassland sites with little or no woody vegetation. The quantity and complex nature of organic carbon found in ecosystems examined in the current study explains the positive relationships between MWD of aggregates and TOC in the surface and subsoils (Bossuyt et al. 2001; Tisdall & Oades 1982; Wilson et al. 2009).

In this study, TOC was lowest in grasslands and positively correlated with litter cover and biomass, plant cover and total cover. The canopies of wooded vegetation types sampled in this study were dominated by sclerophyllous trees, predominantly *Eucalyptus* species. *Eucalyptus*-dominated sites sampled in this study, especially river red gum and some coolibah sites, contained very large old trees, some in excess of 3 m diameter at breast height (DBH). These trees produce large quantities of litter and much larger quantities of coarse woody debris (high C:N) than other vegetation types (Smith and Reid 2013). The woody debris and leaf litter in these sites breaks down slowly (Mackensen et al. 2003; Swift et al. 1979), providing a large sustained input of organic material for decomposer organisms. In contrast, grasslands produce litter with lower lignin content and C:N ratios, which rapidly decomposes and may be lost to the atmosphere through UV-B decomposition (Moorhead and Reynolds 1989). The longer residence time and sustained C inputs to the soil explain the build-up of TOC in wooded ecosystems through time.

The soils in river red gum communities showed greatest aggregate stability, with high MWD scores reflecting the abundance of large aggregates retained on the top sieve (mesh size of 2 mm). Most of the river red gum sites had high soil organic carbon contents compared to other vegetation types; the high MWD score is a hallmark of vertosols under long term organic carbon accession. River red gum communities occur in frequently flooded riparian areas and depressed floodplains across the study region. Riparian sites are biologically active, particularly in semi-arid areas, and can have significantly higher net primary productivity (NPP) compared to ecosystems in the surrounding landscape (Naiman et al. 2005). The majority (>60%) of the carbon stored in the river red gum sites examined is held in the woody biomass and associated components including coarse woody debris, litter and dead standing trees (Smith and Reid 2013) and these components contribute significantly to TOC. However, we do not know what percentage of the soil C is derived from the vegetation in situ as opposed to that which is deposited by flood waters. The riparian sites in this study were dominated by large old trees that had likely been present and contributing large amounts of organic matter to the soil and influencing soil properties for centuries. In the case of such trees, even long after an individual tree dies, its influence on soil properties continues for some time as the accumulated complex organic matter breaks down and decomposes (Tongway et al. 1989).

ASWAT measures the propensity for soil dispersion and includes a wet-shearing treatment (Field et al. 1997). ASWAT in both surface and subsoils was strongly influenced by soil chemistry, particularly Ca^{2+} and Na^+ concentration and ESP. Calcium is an important determinant of soil structure and microaggregate stability (e.g. Emerson 1967; Emerson 1983; Rengasamy et al. 1984; Rengasamy and Olsson 1991). Our data confirm the findings of others, that is, that organic carbon and Ca^{2+} work together to stabilise soil aggregates at macro and micro scales, respectively (Bennett et al. 2014; Loveland and Webb 2003; Rengasamy et al. 1984).

We found that Ca^{2+} was positively correlated, and Na^+ was negatively correlated with TOC in surface and subsoils. Bennett et al. (2014) observed increased soil function and vegetative growth 12 years after the application of gypsum and lime on a red sodosol, and concluded that the initial addition of Ca^{2+} to the soil increased soil function and stability. We believe our data indicate that the presence of large amounts of TOC may increase the availability of Ca^{2+} in the soil and therefore contributes to microaggregate stability (Chorom and Rengasamy 1997; Vance et al. 1998). The likely explanation for this is the influence of TOC in raising CEC and lowering pH in the soil (Bennett et al. 2014).

Organic carbon contributes to formation and stability of interaggregate binding in other soil types (Naidu et al. 1996). The results of this study confirm this principle in vertosols. However, the proportion, type and properties of clay minerals present in these vertosols (i.e. montmorillonite) require higher concentrations of organic matter than other soil types to achieve adequate aggregate stability. Native vegetation dominated by structurally and biochemically different plant life-forms is likely to differentially affect organic matter dynamics, with consequent effects on soil stability (Oades 1984).

Soils under vegetation with a high litter input, especially where litter had a high C:N ratio (i.e. in *Eucalyptus*-dominated sites), showed greater aggregate stability than soils subject to less litter input.

Litter management and, in particular, incorporation of *Eucalyptus* litter in soil increases macroaggregate stability and may therefore be useful in the amelioration of erosion-prone sites. Carbon accession and litter decomposition increases soil CEC and macrofaunal community activity, which in turn increases soil resistance to dispersion (Lavelle and Spain 2001). Planted vegetation sites showed significant litter inputs and further research is required to quantify the potentially beneficial effect of plantings on soil aggregate stability, and determine over what time-scale this occurs. Well-managed grassland sites provide significant litter inputs to soil, but as grass litter is likely to have a simplified carbon structure (and lower C:N ratio) than woody litter (Lavelle and Spain 2001), it may not be as affective in stabilising soils as *Eucalyptus* litter.

Carbon turnover rates and how such rates in turn influence aggregation processes in different land uses may be pivotal in determining both soil stability and resilience to degradation over time. Recent work suggests that residence time of C in soils may be directly linked to aggregate size, with larger aggregates increasing residence time of carbon inputs (Rabbi et al 2013, Rabbi et al 2014a). This has yet to be explored for vertosols, but may be an important factor in explaining time scales of soil stabilisation in both native and managed systems. Aggregation has not typically been the focus of the recent large scale soil carbon surveys in Australia, but proxies such as texture are commonly found to be influential in carbon retention across numerous land uses (Rabbi et al 2014b). A focus on the link between aggregation, carbon residence time, and carbon sources across native and managed land uses in the future may yield valuable information on the potential for soil carbon storage that has gone unexamined to date.

It is unlikely that grasslands generate the quantity and quality of litter produced by woody-dominated communities, and are therefore less able to contribute to soil aggregate stability and erosion mitigation via this mechanism. Litter inputs in semi-arid grasslands are likely to be more pulsed as a result of sporadic rainfall and drought, and the senescence and wind dispersal of above-ground plant matter in dry times. However, grass and litter derived from grasses play an important role in protecting of the soil surface by presenting a physical barrier to water movement.

Stabilisation of surface macroaggregates in vertosols was achieved with 3.0–3.5% TOC brought about by long-term litter deposition and decomposition beneath woody-dominated vegetation. Differences in soil TOC concentrations and complexity were apparent between vegetation types. Slaking is not an inevitable trait of vertosols. As is the case with most other soil types, the degree of slaking in vertosols as measured by macroaggregate stability in water, can be reduced through input of sufficient high-quality (i.e. high C:N ratio) organic matter. With regards to clay dispersion, organic matter reduced the susceptibility of soils to dispersion and hence erosion through its influence on soil chemistry.

River red gum water use and causes of dieback

These data have not been formally analysed. However, the two figures below tell the story pretty well. In January 2014 during a record heat wave, river red gums at Myall Vale were relying on groundwater (Figure 7). Trees close to the river were likely using some river water as well, although it is difficult to say this for sure as there is good ground water – surface water connectivity in the vicinity of the site (travelling stock route at the junction of Spring Plains Road and the Kamilaroi Hwy). No soil water was being used by the trees. The soil at the time was very dry and we struggled to get enough water for isotope tests from 1 m deep soil samples. Given the nature of heavy clay soils, the little water that was present would not have been available to the trees. However, evidence from trees near Boggabri that are currently instrumented with telemetered sap flow meters suggests that river red gums take advantage of soil water when it is available (Figure 8). The example here clearly shows a tree’s water use increased after a large rainfall event in early November. The tree used soil water opportunistically and used that water to put on new leaves (R. Smith pers. obs.). The rainfall event also stimulated the tree to flower and presumably, an increase in DBH followed as well. Interestingly, both the day and night time tree water use increased following rainfall. However, almost a month later, it appears that a lack of follow up rainfall has meant the tree is now looking for water once again, and will presumably start using groundwater once again. Given the use of surface soil moisture at different times by river red gums, we believe that landholders observations of poorer tree condition at sites heavily infested by lippia may hold some merit. However, an addition interaction with grazing needs to be investigated as poor tree health is often seen where heavy grazing occurs. This may be due to compaction of the soil by livestock, or increased prevalence of lippia. Water stress leaves trees open to other types of damage, such as insect attack as is currently being seen near Boggabri with a recent psyllid outbreak.

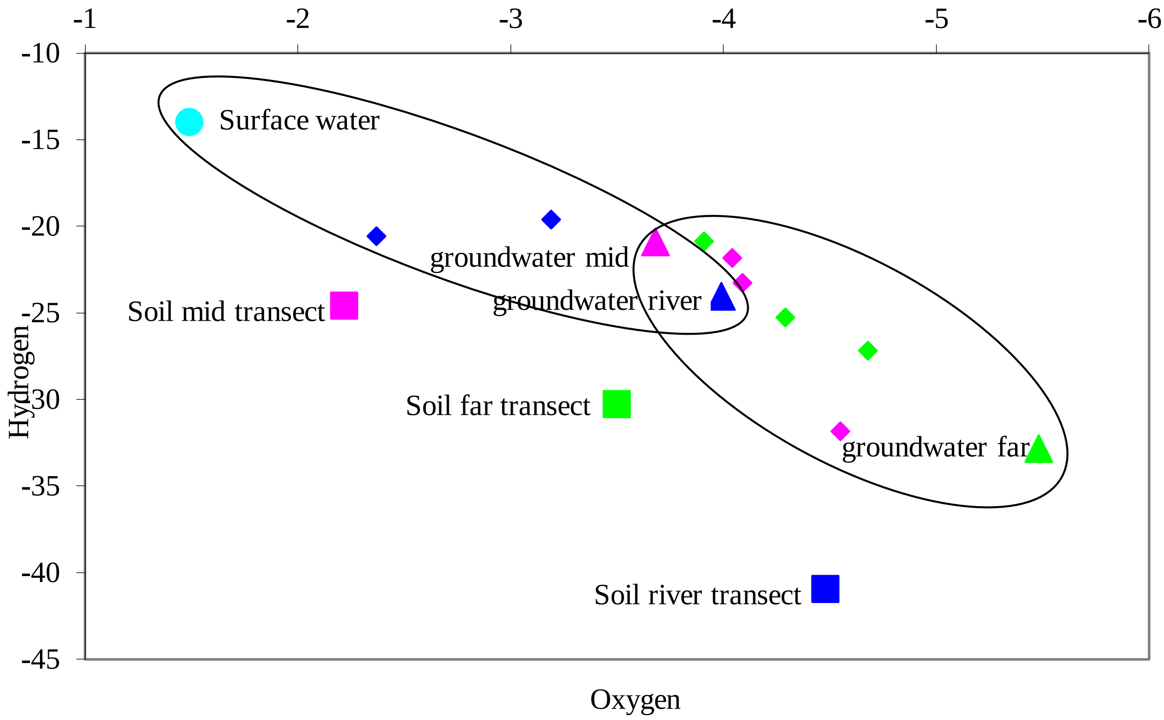


Figure 7: O and H isotope signatures of surface, soil and ground water compared to trees at Myall Vale, January 2014. Circle = surface water, squares = soil water, triangles = ground water and diamonds = trees.

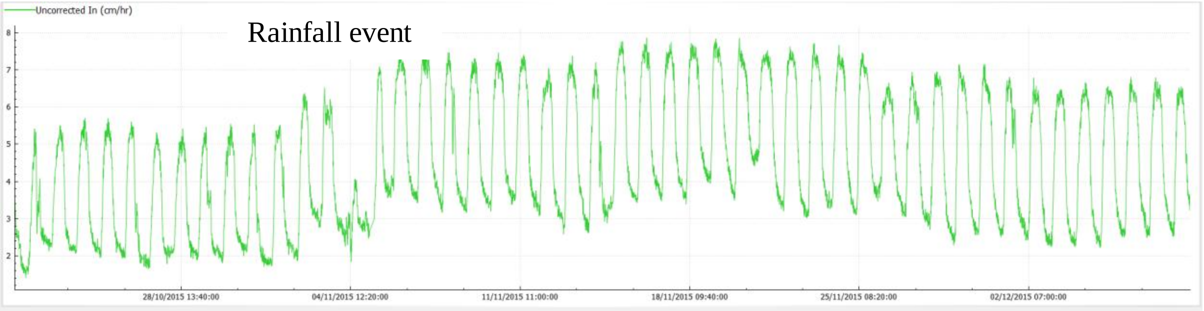


Figure 8: Sap flow velocity (Y-axis) recorded on a tree near Boggabri (9/10/15–20/12/15; X-axis). Note the change in water use after a rainfall event on the 4th November as the tree takes advantage of available soil moisture.

River red gums are long-lived, with reports the trees could reach 500 to 1000 years of age (Gill 1971; Jacobs 1955). Large amounts of water are required to sustain river red gums, with studies showing that river red gums can transpire more than 2000 mm yr^{-1} (Marshall et al. 1997; Thorburn et al. 1993). Given the distribution of river red gums in arid and semi-arid regions, these trees must rely on groundwater and overland flows (i.e. flooding) to supplement low rainfall conditions (Beadle 1981). Studies on the Chowilla floodplain found that river red gums are opportunistic users of water, and may be able to switch between water sources when alternate water sources (i.e. soil water after rainfall) are available (Mensforth et al. 1994). Groundwater is the preferred water source for river red gums as it is more reliable than surface water in terms of availability (Bacon et al. 1993; Thorburn and Walker 1994).

The boom–bust nature of Australian inland floodplain rivers means that river red gums have experienced long periods of drought during their evolutionary history of 2.5 to 5 million years (Crisp et al. 2004) and in response, have developed a range of strategies to deal with water stress. Strong roots and high root-to-shoot ratios allow river red gums to penetrate the soil profile in search of suitable soil conditions (i.e. well aerated soil during floods) and persist in tight, heavy clay soils

(Jacobs 1955). Multiple tap roots of river red gums can extend to a depth of more than 10 metres (Bacon et al. 1993; Davies 1953) and their surface root system can extend at least 20 metres radially from the tree (Dexter 1967). This extensive root system allows river red gums to forage for water and nutrients over a large area. River red gums will adjust evapotranspiration rates in response to heat and water availability (Heinrich 1990; Thorburn and Walker 1994). Studies have shown that river red gums with access to abundant or reliable water sources show lower water use efficiencies than plants relying on variable water sources (Thorburn and Walker 1994). That is, trees with more water available to them for even a short period of time will use that water to promote growth and increase canopy condition in readiness for times when water is less abundant. Declines in water availability promote leaf shedding and branch fall to reduce canopy water use in times of extreme water shortage (Roberts and Marston 2000). Canopy density may be restored through the production of epicormic growth once more favourable conditions return. In marginal environments or prolonged low water conditions, river red gums can reduce their active sapwood area to lower water requirements (Doody et al. 2015).

In addition to natural variability in water availability, human demands for water compound dry conditions in many regions where river red gums occur, resulting in prolonged and severe tree water stress (Horner et al. 2010). Water stress results in embolisms in the water-conducting tissues within the trees (cavitation), which may cause permanent injury and hamper the ability of trees to recover when conditions improve (Jackson and Grace 1994). To a point, river red gums can avoid cavitation by closing stomata to reduce stomatal conductance and maintain xylem pressure (Sperry et al. 2003). There is much speculation around how much water is required to sustain river red gum trees with different studies producing different results depending on tree density and starting condition of the trees.

Vegetation surveys

This data is yet to be analysed as we still have some plant some specimens to be identified, we know that more than 200 plant species were recorded during surveys. While many of the plant communities we conducted surveys in are listed as threatened, vulnerable or endangered, no individual plant species of conservation concern was recorded. This data set will be analysed and published in the context of the bird data in coming months, and will be included in a paper to be published under a subsequent FRP.

Bird surveys

Approximately 192 species were recorded during bird surveys in Spring 2014. Several declining, vulnerable and endangered birds were recorded in surveys, including: painted honeyeater, grey-crowned babbler, crested shrike-tit, black-chinned honeyeater, hooded robin, red-capped robin, rufous whistler and eastern yellow robin. All of these species are insectivorous to some extent and could therefore be important in providing natural pest control services. Greatest bird numbers and diversity were recorded in the Emerald region and there were very clear north–south and east–west gradients in the data. The analysis of this data is very complicated due to the myriad of variables involved in explaining the patterns in bird community composition and abundance of individuals. We found a very strong influence of noisy/yellow throated miners in the data, with smaller birds being less abundant or absent from sites with large numbers of miners. We will explore miner abundance as a potential indicator of site condition for bird biodiversity conservation. Papers are currently underway and have been written into a subsequent FRP.

Habitat condition

This dataset is currently being analysed with respect to vegetation type and a range of environmental variables (location, climate, site management, surrounding land use, etc.). Here we have included a summary of the dataset collected from nine vegetation types and 200 sites. This data is likely to be most useful to grower and the industry on a site by site or region by region basis. Nevertheless, the data shows that canopy cover is highest in river red gum riparian areas and as a consequence, the number of hollow-bearing trees, dead standing trees and logs are also high in this vegetation type. Mistletoes are in greatest abundance in myall vegetation. Given mistletoe is an important food source for many small birds, including the state and federally-listed painted honeyeater, this is noteworthy. Outside of planted vegetation, tree seedlings (natural regeneration) was highest in belah, with some regeneration also recorded in brigalow, coolibah, poplar box and river red gum sites. Again, this is an important component of ecosystem function, necessary for replacement of old senescent trees.

Table 10: Average habitat condition data across 200 sites

Vegetation type	Canopy	Tall shrub	Tree seedling	Mistletoe	Low shrub	Litter	Herbage	Hollow trees	Dieback class	Dead standing trees	Cut stumps	Logs	Bare soil
Belah	31.4	28.1	4.7	0.4	16.7	26.3	49.6	0.2	1.2	0.79	0.1	17.3	25.7
Black Box	33.6	7.0	0.5	0.3	3.5	23.6	49.9	0.7	1.5	0.8	0.2	12.3	25.0
Brigalow	19	46	1.6	0	42.5	16.5	41	0.3	0.6	0.7	0	16.6	33
Coolibah	28.1	11.6	1.5	0.2	6.2	28.7	47.1	0.3	1.3	0.6	0.0	14.3	23.8
Grass	1.6	1.7	0.1	0.0	5.2	17.4	63.5	0.0	0.2	0.0	0.0	2.5	16.7
Myall	19.6	7.3	0.4	1.1	6.4	25.7	53.2	0.0	0.9	0.4	0.0	7.3	21.6
Planted	45.3	16.1	6.0	0.1	10.3	41.9	43.5	0.0	0.9	0.2	0	2.4	14.6
Poplar Box	37.8	9.9	1.5	0.4	7.2	22.6	63.7	0.7	1.6	0.7	0.0	11.5	13.8
River Red Gum	43.3	13.2	1.5	0.2	4.3	23.8	61.5	0.9	1.5	1.0	0.1	22.1	14.6

A simple Principal Components Analysis (PCA) of habitat condition variables shows the greatest amount of variability in the data is explained by canopy cover and associated variables (logs, dead standing trees) while the second-ranked axis of variation is associated with herbaceous vegetation cover. There is a negative relationship between canopy cover and herbaceous vegetation cover.

Table 11: PCA of habitat condition variables at 200 sites on cotton farms across Queensland and NSW

Eigenvalues

PC	Eigenvalues	%Variation	Cum. %Variation
1	3.44	26.4	26.4
2	2.13	16.4	42.8
3	1.5	11.6	54.3
4	1.24	9.5	63.9
5	0.99	7.6	71.5

Eigenvectors

(Coefficients in the linear combinations of variables making up PC's)

Variable	PC1	PC2	PC3	PC4	PC5
Canopy	**0.424**	-0.035	-0.278	-0.035	0.037
Tall shurb	0.291	0.294	0.234	**0.381**	-0.067
Low shrub	0.081	0.310	0.353	**0.433**	-0.387
Herbage	-0.281	**-0.451**	-0.091	0.413	-0.044
Logs	**0.409**	-0.186	0.198	0.093	-0.028
Bare soil	0.043	0.267	**0.522**	-0.501	0.140
Litter	0.305	0.297	**-0.442**	-0.142	0.035
Cut stumps	0.114	-0.189	0.115	**-0.273**	-0.145
Dieback class	**0.330**	-0.281	-0.037	-0.117	0.083
Dead standing trees	**0.327**	-0.206	0.215	0.077	-0.005
Hollow trees	0.320	**-0.417**	0.086	-0.020	-0.160
Tree seedling	0.223	0.296	**-0.375**	0.169	-0.056
Mistletoe	0.083	0.015	0.137	0.305	**0.874**

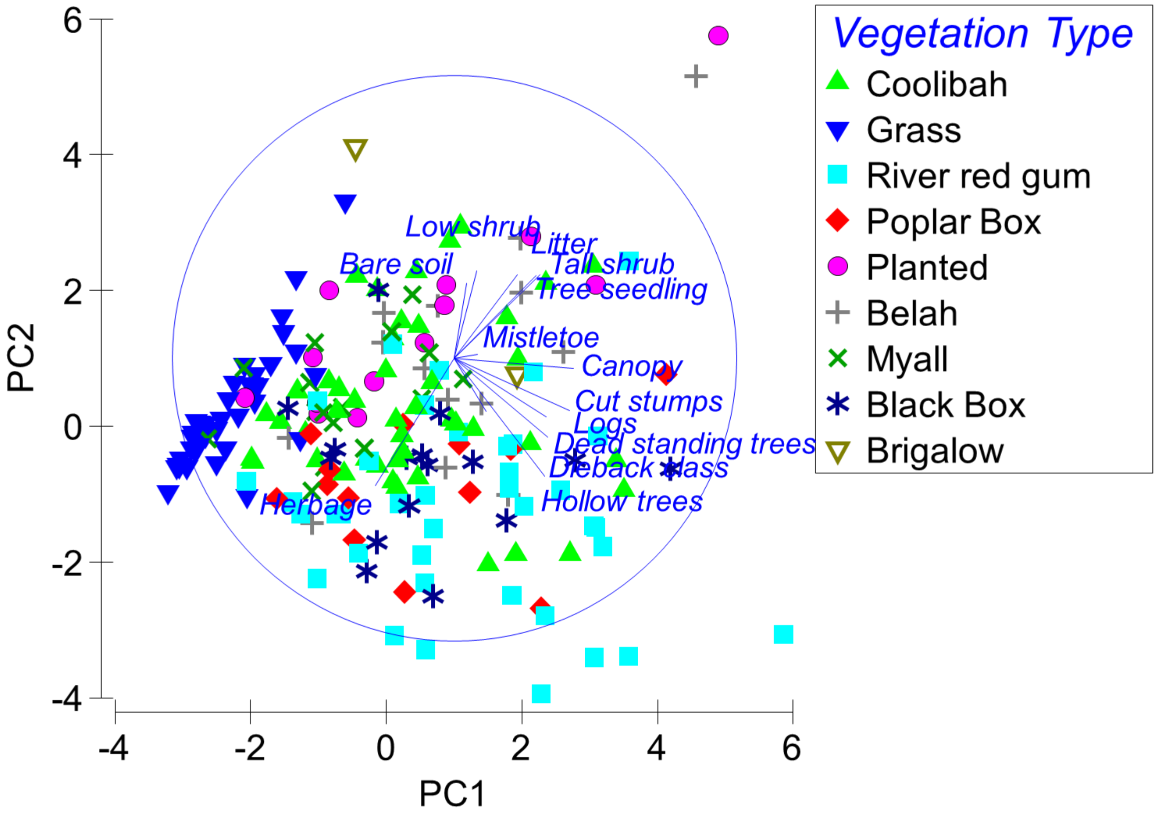


Figure 9: PCA graph showing the habitat condition data by site and vegetation type and site. Note the two main axes in the data are described by (1) canopy cover and associated variables, and (2) herbaceous vegetation cover.

Conclusion

5. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

This research project has illustrated the immense value of native vegetation, particularly riparian vegetation, in providing a range of ecosystem services that benefit both cotton growers and the general public. We have collected baseline data across the extent of the industry on biodiversity (native vegetation and birds) and habitat condition on cotton farms. We have also collected information on the carbon stored by native vegetation and soils under native vegetation across the industry to aid in carbon accounting. We have illustrated the carbon sequestration benefits of native vegetation, particularly riparian vegetation in helping growers achieve carbon neutral cotton farms, and have shown the value of carbon in terms of aggregate stability on vertosol soils. Finally, we have started to investigate water use and potential causes of dieback in river red gums in the Namoi and Gwydir, and will build on that work in a subsequent FRP that has recently commenced.

The information gained through this project will be invaluable to the cotton industry in illustrating concern for natural assets on cotton farms. Baseline biodiversity data can be used in future sustainability reporting, or used in publicity illustrating the number of vulnerable, threatened, and endangered birds residing in native vegetation on cotton farms. Cotton growers make an invaluable contribution to biodiversity conservation by maintaining and preserving native vegetation on farm, and this effort could be rewarded through Biobanking and environmental stewardship programs. Such data could also be particularly valuable in promoting the industry's social licence to farm.

This project has provided data for growers that are interested in minimising their environmental footprint, and potentially reaping economic benefits from management actions informed by science. In addition, this project has created awareness amongst growers of the potential interactions between their operations and the natural environment. In particular, the carbon neutral cotton farms component of the project (in partnership with Francois Visser, Jon Welsh and others) has shown that native vegetation is of vital importance in offsetting carbon emissions from crop production. It is likely that a future emissions reduction scheme or carbon tax will include agricultural activities, and this project has illustrated the potential for cotton growers to avoid taxes through management of native vegetation, while producing a product that appeals to environmentally conscious consumers. All information and data obtained during this project will be used to update best management practices in the industry's myBMP Natural Assets module.

Extension Opportunities

6. Detail a plan for the activities or other steps that may be taken:
(a) to further develop or to exploit the project technology.
(b) for the future presentation and dissemination of the project outcomes.
(c) for future research.

Information and data obtained during this project will be used to update best management practices in the industry's myBMP Natural Assets module. A number of extension materials have been developed with CottonInfo and we will continue to work with Stacey and Jon to extend the findings of this project where relevant. Information will also be fed into the industry's carbon accounting tool and we will continue to work on carbon case studies ad hoc as opportunities arise. Conversations regarding use of the vegetation condition data we collected are planned with Stacey in 2016.

The subject of an ecosystem services session at the 2016 Australian Cotton Conference has been suggested to highlight findings from this and other projects (Nancy Schellhorn and others) on ecosystem services. A conference on environmental restoration, revegetation and ecosystem service provision in agricultural landscapes is also currently being planned at the University of New England to showcase everything that has been learnt during the Brigalow Nandewar Biolinks project and to share experiences with practitioners and academics from around Australia. This includes experiences from studies conducted by our PhD students on cotton farms in the Gwydir and Namoi growing regions. The conference will be held in February 2017.

Given the importance of riparian ecosystems for a range of ecosystem services, a subsequent FRP has commenced to investigate the health of river red gum-dominated riparian ecosystems and formulate management actions that can be undertaken by growers to improve the health of this significant vegetation type.

9. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

Smith, R. and Reid, N. (2013) Carbon storage value of native vegetation on a subhumid–semi-arid floodplain. *Crop and Pasture Science* 64 (12), 1209–1216.
Smith, R., Visser, F., Welsh, J., Vogel, S., Trindall, J. (2014) Carbon neutral cotton farms. *Proceedings of the 17th Biennial Australian Cotton Conference*, Broadbeach, August 2014.
Smith, R., Tongway D., Tighe M., Reid N. (2015) When does organic carbon induce aggregate stability in vertosols? *Agriculture Ecosystems and Environment* 201, 92–100.
Smith, R., Renton, M. and Reid, N. 'Growth and carbon sequestration by remnant *Eucalyptus camaldulensis* woodlands in semi-arid Australia' to be submitted in Dec 2015 to *Agricultural and Forest Meteorology*

Two papers on bird biodiversity on cotton farms will be drafted in the first half of 2016. One of these papers will describe the variability in bird fauna between two time periods (20077 and 2014), the other will describe the impact of vegetation structure on miner communities, and the flow on implications for small woodland birds. Analyses for a third paper reporting the entire bird data set collected in 2014 are currently being investigated. An additional paper investigating the relationship between soil carbon content and aggregate stability on four different vertosols is currently being drafted for submission in 2016. A literature review on the causes of river red gum dieback will be submitted to CRDC in January 2016 for review (once it has been formatted to comply with UNE publication standards).

B. Have you developed any online resources and what is the website address?

N/A

Part 4 – Final Report Executive Summary

This project has investigated some of the ecosystem services provided by vegetation types commonly encountered on cotton farms in eastern Australia. Much of the project has concentrated on carbon and the benefits emanating from carbon-rich soils, given the potential for growers to benefit from payments through carbon markets. The Australian Cotton Industry is developing a carbon (C) footprint calculator for cotton farms to determine C sequestration and emissions associated with agricultural production (irrigated and dryland crops and grazing enterprises), as well as the net primary productivity (NPP) and C sequestered by native vegetation. Data on carbon sequestration by native vegetation from this project has been included in the calculator.

Data collected in this project suggest that river red gums can grow up to 6 cm (diameter at 1.3 m aboveground) per year and sequester just over 2 t $ha^{-1}yr^{-1}$ of C in woody biomass alone during high-rainfall and flood conditions. In addition, river red gum vegetation stored more carbon than other vegetation types, including in the soil, where up to 5% organic carbon content has been measured in the surface 5 cm of soil. Trees in riparian zones generally grow faster than trees on the floodplain and trees in dense stands grew slower than widely-spaced trees. Healthy crown condition was associated with greater growth in trunk diameter. While stem increment decreased with tree size, C sequestration increased, illustrating the importance of mature and old-growth trees as C sinks. This study highlights the contribution of semi-arid riparian woodlands for sequestering large amounts of C during above-average rainfall periods and the need to factor this important sink into global C budgets.

It has been a long-held belief that a degree of slaking upon rapid wetting of aggregates is an inherent trait of vertosols, regardless of OC content. This is attributed to their physico-chemical attributes (e.g. high clay content, shrink–swell capacity, cation exchange capacity and pH). However, studies investigating the erodibility of vertosols have concentrated on cropping soils, usually with low OC content (≤2%). Therefore, the importance of OC in maintaining structural stability and minimising erosion in vertosols has been dismissed. This study examined vertosol macroaggreate and microaggregate stability in natural ecosystems where OC can be >2%. We found a positive relationship between macroaggregate stability and OC content in vertosols, especially when OC was ≥3.5% in the surface soil (0–5 cm). Microaggregate stability was attributed to the dominance of Ca^{2+} over Na^{+} on clay-exchange sites. OC was positively correlated with Ca^{2+} and negatively correlated with Na^{+} and ESP. OC may play a role in microaggregate stabilisation through its capacity to lower soil pH and increase the availability of Ca^{2+}. We demonstrate that OC can stabilise vertosol aggregates, and is therefore important in preventing erosion on this soil type. As such, growers should monitor and manage soil carbon reserves, particularly in erosion-prone lands.

We have shown that river red gums use groundwater during dry conditions, but may switch to soil water where available. This is possible due to a dual root system of deep sinker roots and an extensive surface root system. While river red gums have evolved with drought and have developed mechanisms to deal with drought, the length and intensity of drought has increased and new threats such as lippia and insect attack are further impacting tree health. River red gum vegetation in good condition provides habitat for a range of bird species of conservation importance, many of which are insectivorous and therefore may be important in providing other ecosystem services, such as natural pest control. Riparian vegetation is also the most productive, in terms of biomass, in semi-arid landscapes. It is therefore important that greater effort is put into understanding and managing riparian lands so that landholders may benefit from the ecosystem services they provide. A subsequent FRP will therefore concentrate on management of riparian lands to increase the health of river red gums to maximise ecosystem service provision.

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