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Effects of land-use change and management on soil carbon and nitrogen in the Brigalow Belt, Australia: I. Overview and inventory

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Abstract. Soil and land-management interactions in Australian native-forest regrowth remain a major source of uncertainty in the context of the global carbon economy. We sampled soil total organic C (TOC) and soil total N (TN) stocks at 45 sites within the Brigalow ecological community of the Brigalow Belt bioregion, Queensland, Australia. The sites were matched as triplets representing three land uses, specifically: uncleared native brigalow forest ('Remnant'); grassland pasture ('Pasture'), derived by clearing native vegetation and maintained as pasture for a minimum of 10 years, and; regrowing native brigalow forest ('Regrowth', stand ages ranging from 10 to 58 years) that had developed spontaneously after past vegetation clearing for pasture establishment. Soil TOC fractions and natural abundance of soil C and N isotopes were examined to obtain insight into C and N dynamics. An updated above- and belowground carbon budget for the bioregions was generated. Average soil TOC stocks at 0–0.3-m depth ranged from 19 to 79 Mg ha^{-1} and soil TN stocks from 1.8 to 7.1 Mg ha^{-1} (2.5th and 97.5th percentiles, respectively). A trend in stocks was apparent with land use: Remnant > Regrowth ≅ Pasture sites. Soil δ^{13}C ranged from –14 to –27‰, and soil δ^{15}N ranged from 4‰ to 17‰, in general reflecting the difference between Pasture (C_4-dominated) land use and N_2-fixing (C_3-dominated) Remnant and Regrowth. Mid-infrared spectroscopy predicted C fractions as a percentage of soil TOC stock, which ranged from 5% to 60% (particulate), 20–80% (humus) and 9–30% (resistant/inert). The geo-referenced soil and management information we collected is important for the calibration of C models, for the estimation of national C accounts, and to inform policy developments in relation to land-resource management undertaken within the Brigalow Belt bioregions of Australia.

Additional keywords: *Acacia harpophylla*, carbon-nitrogen ratio, land clearance, pastures, regrowth, stable isotopes.

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Introduction

Assisted natural regeneration (managed regrowth) in cleared rangelands offers substantial and cost-effective opportunities for carbon (C) sequestration (Evans *et al*. 2015). Managing the regrowth of native forests requires less intensive effort and lower costs than tree planting, and because the naturally adapted tree species are encouraged to grow to maturity, it facilitates multiple benefits besides emissions mitigation. These benefits include diversification of rural income streams, restoration of degraded landscapes, and increased biodiversity. Assuming C credits are worth AUD$15 Mg^{-1} (tonne) CO_2-e, as per Butler and Halford (2015), management of regrowth for C credits could provide net economic benefits across ~3.7-million ha in Queensland, and potentially yield aboveground biomass increases equivalent to up to 6×10^7 Mg (60 Mt) CO_2-e over 10 years, with ongoing sequestration at 1.4×10^7 Mg (14 Mt) CO_2-e year^{-1}. However, relatively little is known about the amount or composition of soil organic C within these systems or their sensitivity to management, so only C pools in biomass and debris are used in the calculation of C benefits from land-use change. Henry *et al*. (2015) noted a high uncertainty associated with impacts of land-use change and soil organic C in grazing lands, with regional-scale spatial and temporal datasets rarely available. Improved understanding of soil organic carbon (SOC) under managed regrowth is important for national policy and C management, including the Native Forest from Managed

Regrowth Methodology Determination (Commonwealth of Australia 2015*a*), which uses the C model FullCAM (Richards and Evans 2000) to calculate baseline and projected scenarios for C pools in plant biomass and debris.

The Brigalow (*Acacia harpophylla* F.Muell. ex Benth. dominant and co-dominant) ecological community within the Brigalow Belt bioregions (Commonwealth of Australia 2013, 2015*b*), of Queensland, Australia, was used as a case study to explore soil C in relation to managed regrowth. Brigalow communities are nationally listed as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth of Australia 1999) as they now occupy less than 10% of their former ~7.5-million-ha distribution (Butler 2009; Commonwealth of Australia 2013). In their review of the benefits of brigalow regrowth in Queensland, Peeters and Butler (2014) estimated forest C stocks in standing aboveground mature brigalow forest of ~50–125 Mg C ha^{-1} and suggested that regrowth accumulates biomass at ~1.9–3.2 Mg ha^{-1} $year^{-1}$ (~3.3–5.5 Mg CO_2-e ha^{-1} $year^{-1}$), although the authors note that this estimation is expected to be limited by conditions including site features (strongly seasonal rainfall, higher maximum summer temperatures, competition) and management (clearing, fire and continuous high grazing pressure). Similar estimates of soil C are comparatively scarce: Dwyer *et al*. (2009) suggested that 'soil carbon stocks in regrowth probably remain at levels of mature forests, however, this remains to be tested', whereas Peeters and Butler (2014) noted that 'management to accumulate carbon in the aboveground biomass is expected also to increase soil carbon stocks'. Variation in the history of brigalow land clearing, land use, climate and environmental conditions, as well as land management goals, which may not be congruent (Dwyer *et al*. 2010), present a challenge for estimating the C sequestration potential of forest regrowth. Peeters and Butler (2014) noted that 'some carbon returns might be traded off with other land uses such as livestock grazing which might limit carbon accumulation rates', although they noted that 'low to moderate levels of livestock grazing appear to be compatible with restoration of brigalow vegetation'. In their global review, McSherry and Ritchie (2013) found that grazing effects on SOC reflected interactions between precipitation, grass and soil type, although they observed that grazing effects may be highly context-dependent and, in the case of tropical grasslands, virtually unstudied (Allen *et al*. 2013). With these complex interactions identified, information regarding the composition and dynamics of SOC would improve the certainty of simulation models that predict different land-management scenarios.

Baldock *et al*. (2013*a*, 2013*b*) outlined methods for measuring soil total organic carbon (TOC) composition as biologically significant fractions based upon their size, extent of decomposition and chemical composition. In addition to these techniques, the measurement of the relative abundance of stable isotopes $\delta^{13}C$ and $\delta^{15}N$ using natural abundance techniques has provided insight into C and N dynamics within soil-plant systems, e.g. under vegetation change in Queensland (Krull *et al*. 2005, 2007), although the interpretation of this technique requires caution (Högberg 1997; Wynn and Bird 2008; Bai *et al*. 2013).

This study, part of the National Soil Carbon Program (Commonwealth of Australia 2015*c*), aims to quantify: (i) soil TOC stocks and fractions (i.e. particulate, humus and resistant/inert components) and (ii) soil properties including total N stocks, natural abundance of soil C and N isotopes within the brigalow ecological community of the Brigalow Belt bioregion of Queensland. Results from this study are added to literature values to provide an updated C budget for these bioregions. Further, our findings are used in a companion study to explore the relationship between soil C, soil N and the cycle of tree-clearing, grazing, and natural regeneration of trees within the Brigalow Belt bioregions, Queensland (Pringle *et al*. 2016).

Materials and methods

Site selection

A desktop exercise was undertaken to identify the most-accurate spatial coverage of major soil and vegetation groups within the Brigalow Belt bioregions, Queensland, focusing on the Brigalow (*Acacia harpophylla* dominant and co-dominant) ecological community (Commonwealth of Australia 2013). Vegetation information, as described within Queensland regional-ecosystem mapping units, was sourced from the State of Queensland 'Carbon Accumulation Through Ecosystem Recovery' project database (Fensham and Guymer 2009; the database includes sites sampled by Dwyer *et al*. 2010). Soil information was sourced from The State of Queensland 'Soils and Land Information' database (Biggs *et al*. 2000), which interprets the best-available Australian Soil Classification at Order level (Isbell 2002) from surveys at different mapping intensities. The approach generated a list of potential sites, stratified by land use and soil–vegetation associations.

Sites were attributed to one of three categories reflecting the history of land management, similar to Fensham and Guymer (2009). Brigalow land that was mostly uncleared was assigned the Remnant category. Cleared land that had been brigalow forest before clearing and had been managed as grass pasture for a minimum of 10 years before sampling was assigned the Pasture category. Areas with young native tree species representing regenerating (e.g. through suckering of lateral roots) brigalow forest on previously cleared land was assigned the Regrowth category. Time elapsed since the last clearing was estimated for each regrowth stand using (where possible) satellite remote-sensed data, historical air photos and landholder comment. For each soil Order, Pasture and Regrowth sites were restricted to locations occurring within 10 km of Remnant sites. Limited information was available regarding grazing intensity; cattle grazing occurred at most Pasture and Regrowth sites, although limited cattle grazing also occurred at Remnant sites.

Soil collection

Prior to soil sampling, ArcGIS (ESRI 2011) was used to create a polygon feature of roughly similar area at each of the candidate Remnant, Pasture and Regrowth sites. Within each polygon feature, 10 random locations for sampling were allocated; an additional 10 random locations for each polygon were allocated as a reserve, e.g. in case field-based validation at any of the first 10 locations identified a discrepancy between the mapped and observed soil Order, or where time permitted sampling of >10 locations.

A differential GPS was used to geo-reference soil profiles collected at the allocated locations. The soil profile was extracted using a percussion-driver fitted with a 0.043-m-diameter push tube. Cores were taken to at least 0.5 m depth and sectioned at intervals of 0–0.1, 0.1–0.3, and 0.3–0.5 m. The soil at each interval from an individual core was sealed in a plastic bag, transported at air temperature during 1–3 days-transit, weighed and then stored at 4°C for processing.

Validation of site classification to soil Order level and compositing procedure for bulk soil analyses

The desktop exercise identified that most sites were mapped at low intensity, with polygons broadly representing recurring patterns of geology, topography, soil and vegetation (Land Systems 1 : 250K scale, density of sites <1 per 100 ha; The State of Queensland 2015*a*). Field observations and laboratory analysis were undertaken to validate whether sampled profiles matched the soil Order identified within the polygon feature (as per Allen *et al*. 2013). Sampled soil profiles were described to Order level according to Isbell (2002). In the laboratory, infrared spectroscopy analysis of the soil profile was undertaken to assess similarity between soil profiles at a site, e.g. where profile descriptions identified either: (i) gradual change in soil characteristics at depth, or (ii) a discrepancy between described and mapped soil Order. For infrared spectroscopy analysis, a subset of soil from each profile was sampled from the upper (0–0.1 m) and lower (0.3–0.5 m) depths, dried and ball-milled. Approximately 5 g of each subsample was analysed using diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) of the mid-infrared region (4000–450 cm^{-1}). To maximise the discrimination of soil type, spectra of the two depth intervals were concatenated for each soil profile. Principal component analysis was undertaken on the combined spectra, to assess the degree of similarity between individual soil profiles within a site. Results from the principal component analysis (>3 dimensions) were visualised in two-dimensional space using a Sammon map (Sammon 1969). Obvious outliers detected visually on both the Sammon map and from visual inspection of the profiles were discarded from the sample replicates. Analysis of soil properties was undertaken on individual soil profiles for each site, with the exception of soil texture and Colwell-P. For these two soil properties, a sample composite (derived from combining subsamples of individual profiles within a site) was analysed. For compositing purposes, individual samples within each depth interval were mixed in proportion to their relative bulk densities, producing a single composite profile for a unique land-use-site combination. The composite profile consisted of three samples, corresponding to 0–0.1-, 0.1–0.3-, 0.3–0.5-m soil depth, for analysis.

Soil analysis for carbon, nitrogen, $\delta^{13}C$ and $\delta^{15}N$ of soil ≤2-mm and soil carbon fractions

Individual samples were weighed, air-dried to 40°C, re-weighed and passed through a 2-mm sieve; any gravel or charcoal >2 mm found within the sample was also weighed. A subsample of each 2-mm sieved soil was ground to <100 µm and analysed for soil total (inorganic and organic) carbon (TC), and total nitrogen (TN) contents by high-temperature combustion (Rayment and Lyons 2011; methods 6B2a and 7A5, using TruMac CN, LECO Corporation, St Joseph, MI, USA). Subsamples were then tested for carbonates using 1 M HCl. If effervescence was detected the sample was treated with H_2SO_3 on a hotplate and analysed a second time for TOC content. Total inorganic C (TIC) was calculated as the difference of TC and TOC. All total C, TOC, TIC and TN contents were reported on an oven-dry mass, determined by their gravimetric water contents at 105°C (Linn and Doran 1984).

Natural abundance of $\delta^{13}C$ and $\delta^{15}N$ in soil was determined using a Flash 2000 Organic Elemental Analyser (Thermo-Fisher Scientific, Scoresby, Vic., Australia) coupled to an isotope ratio mass spectrometer analyser (Isoprime-EuroEA 3000, Isoprime Ltd, Stockport, UK), with 10% replication. Samples containing inorganic carbonates were pre-treated with 1 M HCl for 24 h on a 60°C hotplate before analysis. The isotope ratios were expressed using the 'delta' notation (δ), with units of per mille, or parts per thousand, relative to International Atomic Energy Agency (IAEA) reference material standards with known isotopic composition (Parr and Clements 1991). For C, the Vienna Pee Dee Belemnite standard (IAEA-303; Craig 1953) was used to determined $\delta^{13}C$ using the relationship:

$$\delta^{13}C(‰) = ((R_{sample}/R_{standard}) - 1) \times 1000 \qquad (1)$$

where R is the molar ratio of $^{13}C/^{12}C$ of the sample or standard (Ehleringer *et al*. 2000).

For N, ammonium sulfate standards (IAEA-N-1; IAEA-N-2; IAEA-USGS25) were used to determine $\delta^{15}N$. Equation 1 was applied, but in this case the respective R_{sample} and $R_{standard}$ were the ratios of $^{15}N/^{14}N$ in the sample and atmospheric N_2 (Högberg 1997).

Prediction of TOC fractions

In addition to high-temperature combustion to determine soil TOC content, DRIFTS analysis in the mid-infrared region, combined with multivariate partial least-squares regression analysis, was used to predict TOC content (see McCarty *et al*. 2002 for overview and Bellon-Maurel and McBratney 2011 for critical review). This served as a cross-check between methods, and also allowed us to predict the mass-fractions of TOC: particulate (POC), humus (HOC), and resistant (ROC). Predictions were based on a calibration model that comprised 312 soil samples underpinning the Australian Government Soil Carbon Research Program (Baldock *et al*. 2013*a*, 2013*b*). In brief, TOC was calibrated against measured TOC contents of the ≤2-mm soil, determined as described above. An automated 50-µm sieve shaker system was used to quantify the amount of POC (2 mm–50 µm) and HOC (≤50 µm) fractions. The organic C content of these fractions was determined by high-temperature combustion. The amount of ROC present in the combined POC and HOC fractions was determined by ^{13}C NMR analysis.

Soil analysis for pH, electrical conductivity, particle size, phosphorus

Individual samples were subsampled and measured for pH and electrical conductivity (1 : 5 water; method 4A1 of Rayment and Lyons 2011). For composite soil samples, clay and silt contents

were measured by the hydrometer method (Thorburn and Shaw 1987) and bicarbonate-extractable P ('Colwell-P') was determined by method 9B2 of Rayment and Lyons (2011).

Calculation of soil bulk density and soil stocks

Bulk density of the individual samples was determined using fresh sample weight minus oven-dry soil weight (a subsample of fresh soil was dried for 3 days at 105°C; Linn and Doran 1984) divided by the soil core volume. Samples identified within the Vertosol soil Order were standardised to bulk density at field capacity by applying a model of three-dimensional swelling (Pringle *et al*. 2014).

We estimated stocks of soil TOC (both LECO-measured and MIR-predicted), POC, HOC, ROC and TN on an equivalent soil mass basis, according to the method outlined in Pringle *et al*. (2014). Thus the depth intervals cited throughout are only nominal.

All calculations and projections of data as figures were undertaken using R statistical software (R Core Team 2014).

Carbon budget

An updated C budget, incorporating results from the present study and published literature, was generated for the Brigalow Belt bioregions, Queensland. Nomenclature used within the budget is described in detail by the Australian Government Clean Energy Regulator (Commonwealth of Australia 2015*d*).

Results

Inventory

The desktop analysis identified 51 sites within the Brigalow Belt bioregions of Queensland that had potential for soil sampling. Following landholder consent, 45 sites representing Remnant, Pasture and Regrowth were sampled (Fig. 1). Field classification and DRIFTS analysis of the soil profiles identified 10 sites which differed from the mapped soil Order class. Sampled sites, listed by revised soil Order class, are shown in Table 1.

At low concentrations of TOC, the sum of the MIR-predicted mass-fractions (i.e. particulate (POC) + humus (HOC) + resistant (ROC) fractions) tended to fall below MIR-predicted TOC (Fig. 2*a*). Furthermore, the sum of the mass-fractions was influenced by the amount of carbonate in the soil sample (Fig. 2*b*). The implications of these results were: (i) the MIR calibration under-represented the components of low-TOC soil; (ii) LECO-measured rather than MIR-predicted TOC was selected for all further analyses; and, (iii) mass-fractions were consequently expressed in the form adopted by Rabbi *et al*. (2014), i.e. adjusted to a proportion of the MIR-prediction (with the summation forced to 1.0), followed by an assumption that the proportions were applicable also to LECO-measured TOC.

The concentration of TOC generally decreased with depth in the soil profile (Fig. 3). One Pasture profile, however, showed an unexpected increase in TOC with depth. The sampling record for this profile noted a large amount of coarse charcoal visible at depth in this soil core.

Typical values of soil attributes for the depth interval 0–0.3 m, derived from the laboratory analyses, are presented in Tables 2 to 4. Similar patterns were observed for the 0–0.-1 and 0–0.5-m depth intervals (results not shown). Analysis of general soil properties (Table 2) revealed the following trends: (i) moderately acidic to moderately alkaline soil, although the trend in soil pH with soil depth was inconsistent within each land use and soil Order; (ii) low soil electrical conductivity and Colwell P; (iii) medium-heavy clay content (with the exception of one site in the Remnant category which had a sandy clay-loam texture). TOC and TN stocks tend to be higher in Remnant than Pasture, and $\delta^{13}C$ and $\delta^{15}N$ tend to be higher in Pasture than Remnant (Table 3); formal hypothesis tests about the effects of land-use change on the soil attributes are examined in the companion paper (Pringle *et al*. 2016). The TOC stock is dominated by the HOC fraction (Table 4).

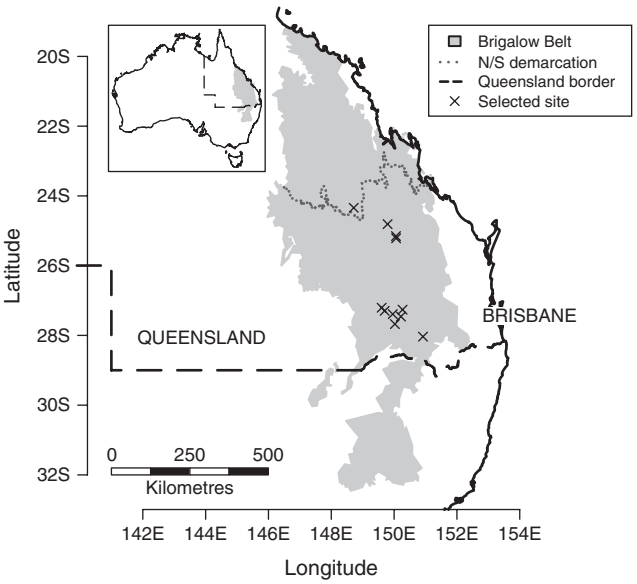

Fig. 1. Plot of sites sampled. Sites (crosses) are located in the Brigalow Belt bioregions (grey). The dotted line denotes the demarcation between Brigalow Belt North and Brigalow Belt South.

Table 1. The number of sites sampled in the Brigalow Belt bioregions of Queensland, listed by land use, age since clearing, and soil Order (Isbell 2002), and the range of years since clearing of remnant vegetation for dominant Vertosol and Dermosol soil Orders

	Vertosol	Dermosol	Sodosol	Tenosol
Land use				
Remnant	7	4	1	1
Pasture	11	2	–	–
Regrowth	5	9	–	–
Years since clearing				
Pasture	18–73	15–34	–	–
Regrowth	21–45	10–58	–	–

Carbon budget

The updated C budget (Fig. 4) suggests an estimated total C (above + belowground) stock ranging between 28 and 365 Mg ha^{-1} in the Brigalow Belt bioregions, Queensland. Areas of highest budget uncertainty are in the Brigalow Belt North.

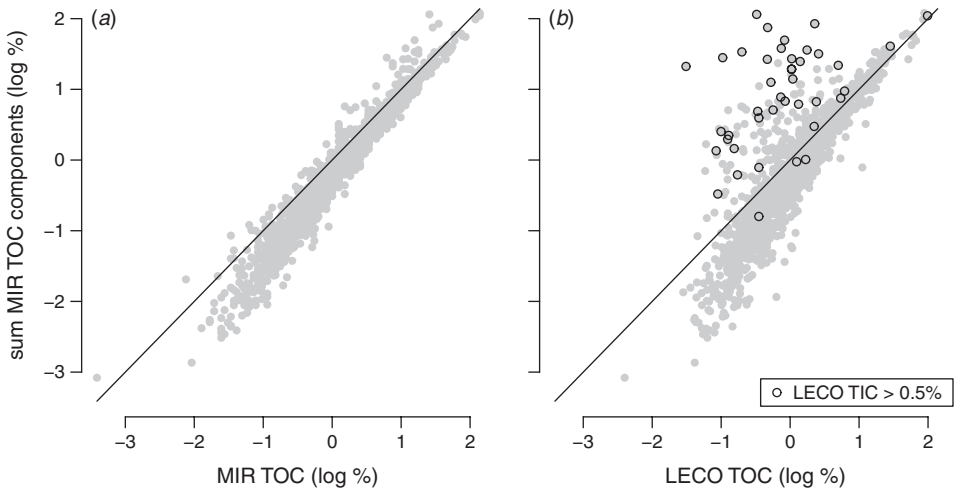

Fig. 2. Scatter plots of (*a*) Mid infrared (MIR) spectroscopy prediction of TOC (*x*-axis) and TOC derived from summation of particulate, humus and resistant carbon components (sum MIR TOC components, *y*-axis) and (*b*) measured (combustion LECO, *x*-axis) and predicted total organic carbon (TOC) derived from summation of MIR-predicted particulate, humus and resistant organic carbon components (sum MIR TOC components, *y*-axis). Units of measurement are shown as concentration (%), expressed as log-transformation.

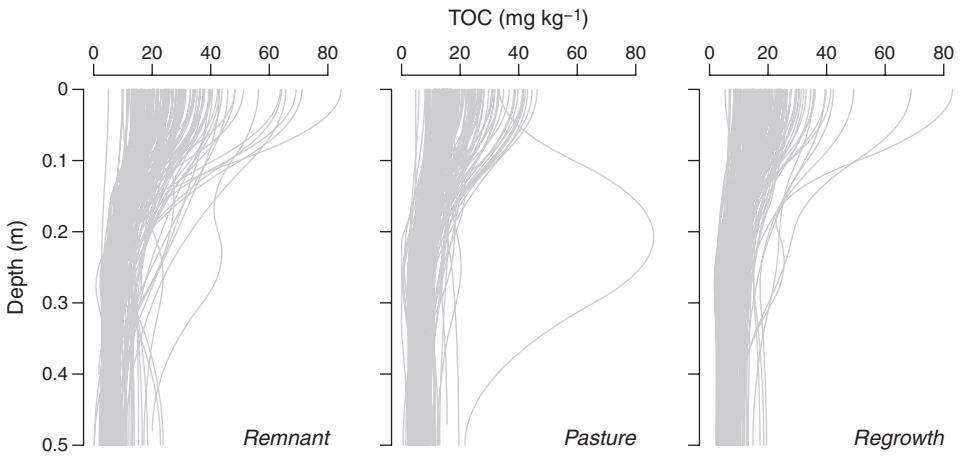

Fig. 3. Concentration of soil total organic carbon (TOC, mg kg^{-1}) with depth (m) for individual soil cores sampled within Remnant, Pasture and Regrowth land use. Note that the data are displayed as equal-area spline predictions as per Bishop *et al*. (1999).

Table 2. Typical values for the depth interval 0–0.3 m, for each combination of soil Order (Isbell 2002) and land use, for measured soil attributes pH, electrical conductivity, clay content and phosphorus (Colwell-P)
Medians are shown, with quantities in brackets denoting the 2.5th and 97.5th percentiles

Soil Order	Land use	pH	Electrical conductivity (dS m^{-1})	Clay (%)	Colwell-P (mg kg^{-1})
Vertosol	Remnant	7.4 (5.3–8.6)	0.18 (0.05–0.56)	48 (42–57)	6.9 (5.2–88.7)
Vertosol	Pasture	7.5 (5.6–8.7)	0.17 (0.05–0.76)	52 (37–59)	10.9 (3.5–132.0)
Vertosol	Regrowth	7.6 (5.5–8.7)	0.14 (0.02–0.76)	44 (31–54)	15.7 (5.1–71.4)
Dermosol	Remnant	7.6 (5.3–8.4)	0.20 (0.08–0.56)	53 (51–58)	27.7 (10.1–36.8)
Dermosol	Pasture	7.8 (6.2–8.6)	0.17 (0.07–0.33)	54 (47–55)	18.6 (5.1–20.0)
Dermosol	Regrowth	6.6 (5.2–8.1)	0.25 (0.05–0.98)	54 (45–59)	13.5 (8.5–18.8)
Other	Remnant	7.2 (6.3–8.2)	0.06 (0.03–0.15)	30 (24–35)	38.4 (13.9–67.4)

Table 3. Typical values for the depth interval 0–0.3 m, for each combination of soil Order (Isbell 2002) and land use, for carbon and nitrogen stocks and natural abundance $\delta^{13}C$ and $\delta^{15}N$

Medians are shown, with quantities in brackets denoting the 2.5th and 97.5th percentiles

Soil Order	Land use	TOC stock (Mg ha^{-1})	TN stock (Mg ha^{-1})	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Vertosol	Remnant	46 (27–116)	3.9 (2.3–9.8)	–23.7 (–25.9 to –21.3)	7.3 (5.5–10.4)
Vertosol	Pasture	35 (22–76)	3.3 (2.3–7.6)	–20.8 (–23.8 to –17.6)	9.5 (6.6–11.4)
Vertosol	Regrowth	43 (27–86)	3.9 (2.5–7.7)	–22.2 (–24.9 to –19.0)	7.3 (5.3–10.1)
Dermosol	Remnant	49 (31–87)	4.2 (3.0–7.1)	–23.5 (–25.0 to –22.0)	9.6 (6.7–11.6)
Dermosol	Pasture	36 (16–56)	3.4 (2.1–4.8)	–22.7 (–24.0 to –21.8)	10.1 (8.8–11.6)
Dermosol	Regrowth	34 (17–55)	3.1 (1.7–4.8)	–24.0 (–26.2 to –21.8)	9.5 (7.2–11.3)
Other	Remnant	47 (26–114)	4.1 (2.1–10.0)	–22.7 (–24.8 to –19.8)	9.1 (7.7–10.8)

Table 4. Typical values for the depth interval 0–0.3 m, for each combination of soil Order (Isbell 2002) and land use, for particulate organic carbon (POC), humus organic carbon (HOC) and resistant organic carbon (ROC) fractions

Mean values are reported to ensure the fractions sum to 1.0. Quantities in brackets are the 2.5th and 97.5th percentiles

Soil Order	Land use	POC fraction	HOC fraction	ROC fraction
Vertosol	Remnant	0.23 (0.09–0.38)	0.57 (0.34–0.74)	0.20 (0.10–0.30)
Vertosol	Pasture	0.22 (0.04–0.62)	0.59 (0.20–0.81)	0.19 (0.07–0.30)
Vertosol	Regrowth	0.28 (0.08–0.61)	0.48 (0.14–0.71)	0.24 (0.15–0.33)
Dermosol	Remnant	0.22 (0.15–0.33)	0.61 (0.49–0.75)	0.17 (0.11–0.22)
Dermosol	Pasture	0.29 (0.17–0.46)	0.56 (0.38–0.69)	0.15 (0.09–0.22)
Dermosol	Regrowth	0.23 (0.07–0.44)	0.63 (0.43–0.82)	0.13 (0.07–0.21)
Other	Remnant	0.24 (0.10–0.48)	0.48 (0.31–0.59)	0.28 (0.19–0.33)

Discussion

Median stocks of soil TOC and TN calculated for our study (34–49 and 3.1–4.2 Mg ha^{-1}, respectively; Table 3) are similar to values reported for Queensland's semiarid *Acacia*-dominated rangelands (Harms *et al*. 2005; Mathers *et al*. 2006; Kirschbaum *et al*. 2008; Dalal *et al*. 2013) and are within the estimates reported for humid sub-tropical to warm semi-arid climates globally (Batjes 1996; Viscarra Rossel *et al*. 2014; de Godoi *et al*. 2016). HOC (<50 µm) comprised around half of the soil TOC in our study (Table 4), which is within the range reported (41–70%) for brigalow forest and conversion to pasture (Dalal *et al*. 2011). The C budget estimated here for Queensland's Brigalow Belt (Fig. 4) aligns with studies reporting lower TOC and TN stocks upon conversion of forest to grassland (Dalal *et al*. 2005; Harms *et al*. 2005; Kirschbaum *et al*. 2008) and long timeframes (>30 years) before comparable TOC stocks between reforested and remnant sites are observed (Cunningham *et al*. 2015). However, there are also reports of no change in SOC stock following clearing of forest to pasture (Dalal *et al*. 2011) or reforestation of pasture to *Acacia* (Oelofse *et al*. 2016). Where no change in TOC stocks occurred, significant differences in POC (Dalal *et al*. 2011) and HOC (Eclesia *et al*. 2012) soil C fractions were observed.

The inconsistency of these results may reflect the different methods adopted to assess variation in TOC and TN stocks, different ages of land-use conversion, initial SOC stocks and comparable land condition. In the absence of longitudinal data (e.g. 'stock-change' method; Toriyama *et al*. 2011), many of the studies deferred to point-in-time measurements using paired-site or chronosequence (space-for-time substitution) approaches. These approaches often assume that sites were the same before a change in land use, particularly in terms of vegetation and soil-forming factors (e.g. Harms and Dalal 2003; Harms *et al*. 2005; Powers and Veldkamp 2005; Cunningham *et al*. 2015). However the influence of local biophysical factors including soil clay minerology can strongly govern the direction and magnitude of change, and require correction (Powers *et al*. 2011; Fujisaki *et al*. 2015). In the Vertosols of the Brigalow Belt, this may be further confounded by carbonate dissolution, although Ahmad *et al*. (2015) note that the research field of soil carbonate equilibrium and transformation is highly uncertain, suggesting future research to 'track the mobility of HCO_3-ions using ^{14}C in conjunction with other suitable methodologies to understand the potential role of carbonates and dynamics in the global terrestrial C budget' is needed. Sanderman and Baldock (2010) note that it can also be difficult to identify the underpinning mechanism of changing TOC stocks, e.g. is a change due to a reduction of C losses rather than an actual increase in inputs? This makes comparisons with longitudinal studies difficult. With these considerations in mind we adopted a novel geostatistical approach (Pringle *et al*. 2016), which accounts for spatial autocorrelation in TOC and TN, as well as the effects of variables such as climate, soil and past land management.

Reducing uncertainty in the following areas will assist land management and policy decisions in the Brigalow Belt bioregions: (i) information on the amounts, decomposability, and turnover of litter; (ii) capturing the variation in methods used to convert brigalow forests to pasture, including regrowth control; (iii) the role of commercial grazing within different stages of brigalow clearing and regrowth management, and; (iv) the capacity to capture model inputs in other Australian bioregions where

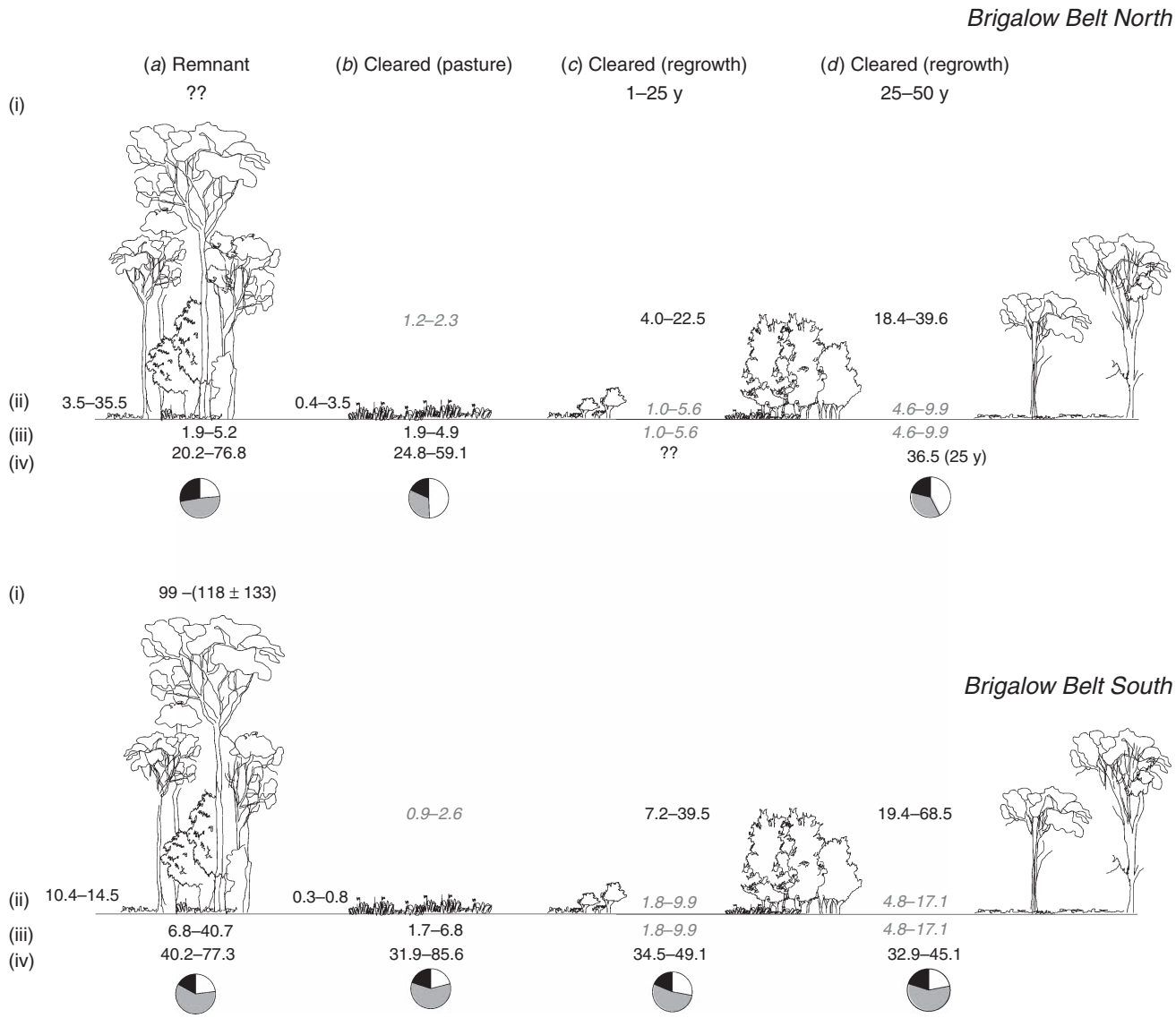

Fig. 4. Schematic of the estimated carbon budget (Mg ha^{-1}) for the Brigalow Belt bioregions, listed according to management categories: (*a*) mostly undisturbed (i.e. remnant); (*b*) remnant cleared for pasture; (*c*) remnant cleared for pasture with brigalow regrowing for 1–25 years; and, (*d*) remnant cleared for pasture with brigalow regrowing for 25–50 years. The carbon budget is denoted as per Emissions Reductions Fund (Commonwealth of Australia 2015*d*) in four components, shown vertically in order of: (i) aboveground, comprising live + dead, (ii) litter and debris, (iii) belowground, (iv) soil organic carbon (TOC) stock 0–0.3 m. Pie charts denote the proportions of soil total organic carbon as particulate (white), humus (grey) and resistant (black) fractions. Estimates shown represent the range of values reported from the following sources: Moore *et al*. (1967); Smith and Grundy (2002); Harms and Dalal (2003); Roxburgh *et al*. (2006); Chandler *et al*. (2007); Dwyer *et al*. (2010); Thornton *et al*. (2010); Ngugi *et al*. (2011); this study. Values in italics for (i) represent the estimated range in values for annual total standing dry matter, based upon modelled time-series graphs for IBRA sub-regions (The State of Queensland 2015*b*). Values in italics for (ii) and (iii) are estimates based upon 25% of aboveground values.

managed native regrowth is of interest. In the absence of historical records, or to strengthen detailed grazing-management histories, it is worthwhile exploring whether FullCAM may be coupled to information from more advanced remote-sensing technologies to quantify vegetation components over time, e.g. multi-resolution time-series imagery to assess the density of tree canopies (e.g. Schmidt *et al*. 2015) or spatial distribution of pasture utilisation (e.g. Pringle *et al*. 2014).

Conclusions

Quantified geo-referenced soil N and C stocks, associated soil C fractions and natural abundance of $\delta^{13}C$ and $\delta^{15}N$ in soil within the Brigalow Belt bioregions, Queensland, are informative for several purposes. They can be used for: calibration of process models associated with national C accounts; improvement of sampling methods, analytical methods and spatial interpolation

of soil properties; greater mechanistic understanding of climate, landscape and management parameters influencing C and N cycling; and collection of physical samples and historical data, which enables future sampling to measure change over time. Continued emphasis linking plant litter and root biomass inputs and soil properties to spatially derived information is necessary to improve model estimation of TOC changes, and to determine whether such changes are related to variation in climate, soil, or management effects.

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