CSIRO PUBLISHING

The Rangeland Journal, 2016, **38**, 229–243
http://dx.doi.org/10.1071/RJ15097

Is land condition a useful indicator of soil organic carbon stock in Australia's northern grazing land?

S. G. Bray[A,F], *D. E. Allen*[B], *B. P. Harms*[B], *D. J. Reid*[A], *G. W. Fraser*[B], *R. C. Dalal*[B], *D. Walsh*[C], *D. G. Phelps*[D] *and R. Gunther*[E]

[A]Department of Agriculture and Fisheries, PO Box 6014, Redhill Rockhampton, Qld 4702, Australia.
[B]Department of Science, Information Technology and Innovation, GPO Box 5078, Brisbane, Qld 4001, Australia.
[C]NT Department of Primary Industry and Fisheries, GPO Box 3000, Darwin, NT 0801, Australia.
[D]Department of Agriculture and Fisheries, PO Box 519, Longreach, Qld 4730, Australia.
[E]Department of Agriculture and Fisheries, PO Box 53, Cloncurry, Qld 4824, Australia.
[F]Corresponding author. Email: steven.bray@daf.qld.gov.au

Abstract. The grazing lands of northern Australia contain a substantial soil organic carbon (SOC) stock due to the large land area. Manipulating SOC stocks through grazing management has been presented as an option to offset national greenhouse gas emissions from agriculture and other industries. However, research into the response of SOC stocks to a range of management activities has variously shown positive, negative or negligible change. This uncertainty in predicting change in SOC stocks represents high project risk for government and industry in relation to SOC sequestration programs.

In this paper, we seek to address the uncertainty in SOC stock prediction by assessing relationships between SOC stocks and grazing land condition indicators. We reviewed the literature to identify land condition indicators for analysis and tested relationships between identified land condition indicators and SOC stock using data from a paired-site sampling experiment (10 sites). We subsequently collated SOC stock datasets at two scales (quadrat and paddock) from across northern Australia (329 sites) to compare with the findings of the paired-site sampling experiment with the aim of identifying the land condition indicators that had the strongest relationship with SOC stock.

The land condition indicators most closely correlated with SOC stocks across datasets and analysis scales were tree basal area, tree canopy cover, ground cover, pasture biomass and the density of perennial grass tussocks. In combination with soil type, these indicators accounted for up to 42% of the variation in the residuals after climate effects were removed. However, we found that responses often interacted with soil type, adding complexity and increasing the uncertainty associated with predicting SOC stock change at any particular location.

We recommend that caution be exercised when considering SOC offset projects in northern Australian grazing lands due to the risk of incorrectly predicting changes in SOC stocks with change in land condition indicators and management activities for a particular paddock or property. Despite the uncertainty for generating SOC sequestration income, undertaking management activities to improve land condition is likely to have desirable complementary benefits such as improving productivity and profitability as well as reducing adverse environmental impact.

Additional keywords: carbon sequestration, pasture management, soil organic matter, uncertainty.

Received 14 September 2015, accepted 29 February 2016, published online 13 June 2016

Introduction

Land condition and greenhouse gas emissions in the north Australian beef industry

Poor grazing land condition reduces pastoral productivity in northern Australia, predominantly through a reduction in the abundance and growth of palatable, perennial forage species available for grazing by livestock (McIvor and Gardener 1995; DPI&F 2004; MacLeod *et al*. 2004; MLA 2005). Poor grazing land condition also impacts on other environmental qualities, including landscape health and water quality (McIvor *et al*. 1995*b*; Bartley *et al*. 2010, 2014), soil organic carbon (SOC) and vegetation C stock (Ash *et al*. 1995; Schuman *et al*. 2002; Northup *et al*. 2005). Grazing land condition therefore plays a central role in the productivity, profitability and sustainability of extensively managed grazing enterprises (MacLeod *et al*. 2004; Orr *et al*. 2010*a*; O'Reagain *et al*. 2011; Scanlan *et al*. 2013). Despite this, substantial areas with poor grazing land condition exist across much of northern Australia's grazing lands (Tothill and Gillies 1992; Shaw *et al*. 2007; Karfs *et al*. 2009*a*; Beutel *et al*. 2014).

Recently agriculture has come under public scrutiny for its contribution to national greenhouse gas emissions, with agriculture responsible for 15% of Australia's total emissions under Kyoto Protocol reporting in 2013 (DoE 2015). The north Australian grazing industry generates significant quantities of methane from livestock (Charmley *et al*. 2008) and has been implicated in the loss of soil and vegetation C through land clearing (DERM 2010) and land degradation (CSIRO 2009). Improving land condition (or ameliorating land condition decline) may reduce the greenhouse gas emissions intensity of grazing businesses (emissions per unit of livestock product) and potentially increase SOC stocks (Bray and Willcocks 2009; Bray *et al*. 2014). Reducing greenhouse gas emissions or sequestering C from the atmosphere into soil or vegetation has potential to offset agricultural and/or other industrial emissions as part of emissions trading schemes (CSIRO 2009; DCCEE 2010). The Australian Government's Emission Reduction Fund (ERF) has approved SOC methodologies (Australian Government 2014), with other methodologies likely to be developed in coming years. Sequestering SOC (or reducing SOC loss) in northern Australia's grazing land relies upon identifying drivers of SOC change associated with management activities at various spatial and temporal scales. Key considerations when deciding to undertake an ERF project will be the ability to reliably demonstrate SOC sequestration within the timeframes of C markets, taking into consideration project duration and permanency requirements. The C price will also be important unless co-benefits such as higher pastoral productivity (Bryan *et al*. 2014) or preventing land degradation are also achieved.

Land condition indicators and SOC

Extensive grazing in the Queensland and Northern Territory regions of northern Australia occupies 207 million ha or 85% of Queensland and 45% of the Northern Territory (Gleeson *et al*. 2012). This vast area is estimated to contain 9.2 Gt of SOC to a depth of 0.3 m (Viscarra Rossel *et al*. 2014). SOC stocks are linked to climatic, soil, woodland and pasture attributes (Bird *et al*. 2000; Allen *et al*. 2013; McSherry and Ritchie 2013; Orgill *et al*. 2014; Viscarra Rossel *et al*. 2014), which are also important factors when assessing land condition (DPI&F 2004; MLA 2005). The ABCD land condition framework is used across grazing land in northern Australia, and assesses land condition in the context of 'soil and vegetation communities' (referred to as 'land type') and rainfall (MLA 2005). The ABCD land condition framework categorises grazing land into A (Good), B (Fair), C (Poor) and D (Very poor/Degraded) condition. Land type and rainfall govern the overarching potential for biomass production, whereas the condition of the land represents the capacity of an area to reach that potential. In general terms, humid tropical and sub-tropical areas have a greater potential to produce pasture biomass than arid areas, and deep fertile soils have a greater potential than shallow infertile soils. All else being equal, pasture biomass production within an area is influenced by soil condition, tree and shrub basal area and canopy cover (Scanlan *et al*. 1996) and perennial grass density, species composition and basal area (Orr and Phelps 2013). SOC stocks are reported as being positively correlated with pasture biomass (Ash *et al*. 1995; McIvor and Gardener 1995; Hunt *et al*. 2014). The implication is that pasture productivity and therefore livestock carrying capacity will be highest in class 'A' land condition and will decline as land condition deteriorates from A to D condition (Table 1; Ash *et al*. 2001). As the ABCD land condition framework provides a basis for assessing pasture productivity, it should be possible to demonstrate a link between the ABCD land condition ratings and SOC stocks.

The ABCD land condition framework has four key components combining several land condition indicators (DPI&F 2004):

- Pasture condition (perennial grass tussock density, species composition, weeds),
- Forage condition (pasture biomass and quality),
- Soil condition (ground cover including pasture and litter cover and soil crust), and
- Woodland condition (tree and shrub density and species composition).

Perennial tussock grasses have been demonstrated to have a strong relationship with SOC stocks in northern Australia. Soil C concentration and microbial activity decline as distance from a perennial grass tussock increases (Holt 1997; Northup *et al*. 1999, 2005; Ash *et al*. 2001). Northup *et al*. (2005) found that the influence of individual tussocks of the main perennial grass (*Bothriochloa ewartiana*) was restricted to a distance of <0.3 m. Scaling the tussock findings up to the paddock or regional scale, higher SOC stocks were associated with large and closely spaced

Table 1. Land condition rating definitions for assessment at the quadrat scale (modified from Stocktake (DPI&F 2004))

At the quadrat scale, tree density was not considered and was measured separately. 3P = perennial, palatable and productive grass

Rating	Description	Productivity relative to A condition
A condition	Good coverage of palatable, perennial and productive (3P) grass species, little bare ground in most years (<30%), few weeds, no erosion	1
B condition	Similar to A condition but with one or more of the following: some decline of 3P grasses, an increase in less palatable or productive species, an increase in bare ground (30–50%) in most years, signs of previous erosion, evidence of current erosion risk	0.75
C condition	Similar to B condition but with one or more of the following: general decline of 3P grasses, large amounts of less palatable or productive species, >50% bare ground in most years, obvious signs of previous erosion, high susceptibility to current erosion	0.45
D condition	Has one or more of the following: general lack of perennial grasses and forbs, severe erosion or scalding (resulting in a hostile environment for plant growth) and/or weeds that cover most of the area	0.2

(abundant) perennial tussocks compared with paddocks with small and sparse perennial tussocks as can occur when land is in poor condition (Ash *et al*. 1995). Lower SOC stock associated with land in poor condition was attributed to a decline in net primary productivity (annual pasture growth). Based on the findings from this research, the theory that perennial grass tussock basal area and tussock abundance determines SOC stock has gained traction among industry advisers and been widely promoted in extension material for land managers to encourage better land management (Ash *et al*. 2001; MLA 2005) as depicted in Fig. 1.

Trees and shrubs also influence SOC, with higher SOC stocks under the canopy compared with away from the canopy (Wilson *et al*. 2007; Waters *et al*. 2015). At the plot or paddock scale, a reduction in tree cover from clearing generally leads to an increase in pasture biomass (Scanlan 2002) and SOC sampling at the paddock scale has shown little or no reduction in SOC stock with tree clearing for pasture development (Guo and Gifford 2002; Dalal *et al*. 2005; Harms *et al*. 2005; Fujisaki *et al*. 2015; Waters *et al*. 2015). Reforestation has also shown little impact on SOC stocks (Marin-Spiotta *et al*. 2009). However, results have been inconsistent with some studies predicting a decline in SOC stocks with the removal of tree canopy cover (Chen *et al*. 2005; Witt *et al*. 2011).

Ground cover, pasture biomass and litter biomass have the potential to modify SOC stocks through the supply of C to the soil and by influencing the rate of SOC decomposition through increased rainfall infiltration, reduced soil evaporation and protecting the soil surface from erosion and soil temperature extremes (McIvor and Gardener 1995; Fraser and Waters 2004; Silburn *et al*. 2011). These factors in turn increase the available soil moisture for plant growth and hence SOC input into the soil. The amount of available soil nitrogen (N) also impacts the amount of biomass grown (Pringle *et al*. 2014; Segoli *et al*. 2015). In northern Australia, greater pasture biomass and ground cover is generally associated with greater abundance of perennial grass tussocks and good land condition (Ash *et al*. 1995; McIvor and Gardener 1995; Hunt *et al*. 2014).

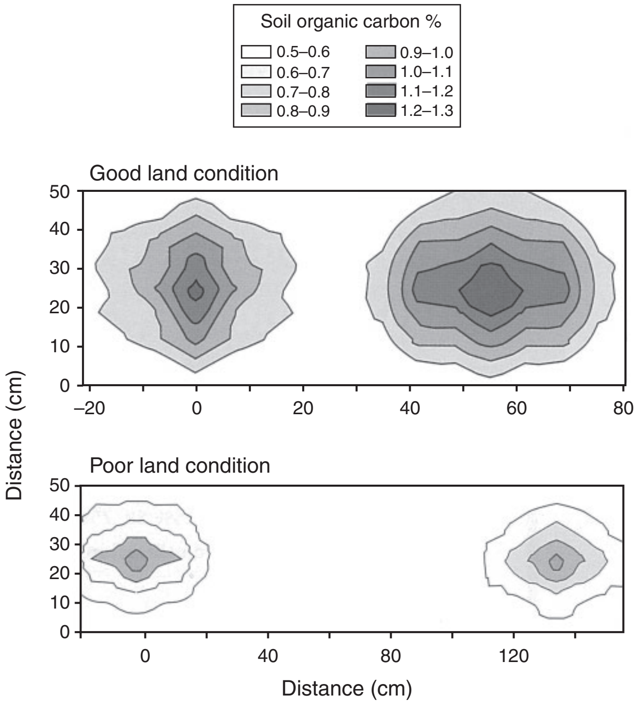

Fig. 1. Depiction of the pattern of soil organic carbon in the top 0.1 m of soil for two land condition states. 'Good' land condition (top) has a high density of large healthy perennial grass tussocks and higher soil organic carbon compared with 'Poor' land condition (bottom) where the density and vigour of perennial grass tussocks has been reduced through overgrazing. Source: Ash *et al*. (2001).

Challenges in relating SOC stocks to land condition indicators

Given the overlap between the drivers of SOC stocks and land condition, we would expect that land condition indicators might represent a powerful surrogate for predicting C stocks in grazing lands. However, variability related to spatial and temporal scales poses a challenge.

Land managed for extensive grazing is renowned for high spatial variability (Allen *et al*. 2010; Pringle *et al*. 2011; Waters *et al*. 2015). The paddock is the basic management unit for extensive grazing properties, and can range from 5 ha to 50 000 ha in northern Australia depending on the management purpose of the paddock and the location and infrastructure of the property. SOC stocks can represent C inputs accumulated from months through to millennia before the present (Krull *et al*. 2005). Thus, a SOC measurement at a single location may not represent either spatial or temporal scales particularly well.

ABCD land condition assessment has generally been undertaken at a 'monitoring plot' scale of 1 ha and scaled to the paddock scale based on field observation. A modified version has been used at the quadrat scale and compared with SOC stocks and water infiltration (Fraser 2013). In one study, SOC stocks in the 0–0.05-m layer were generally lower in poorer land condition classes when assessed at the quadrat scale (Carter and Fraser 2009). However, in a subsequent study, the results were not consistent and the strongest relationship between land condition and SOC stocks only occurred on soils with greater than 60% sand content (Fraser 2013).

The time scale for SOC stock change poses a significant challenge for its prediction and measurement. Total SOC stocks are made up of several soil C pools with mean residence times of months to years for large particle sizes (>200 µm), decades for medium particle sizes (53–200 µm) and millennia for fine particle sizes (<53 µm) and inert C such as charcoal (Dalal *et al*. 2005; Krull and Bray 2005; Krull *et al*. 2005; Krull *et al*. 2007; Zhang *et al*. 2015). There is also a strong relationship between soil depth and SOC residence time. In one example for a Vertosol soil type in western Queensland, mean residence time ranged from 12 years in the 0–0.02-m layer to 500 years in the 0.2–0.3-m layer (Krull *et al*. 2005). These time-scale effects indicate the potential limitations to making rapid changes to SOC from future changes in land management and the potential uncertainty associated with historical land management impacts (e.g. a period of overgrazing).

SOC stocks are a balance of inputs, outputs and flows between SOC pools as part of the global C cycle (Janzen 2004).

Two overarching processes are the magnitude of C inputs and the rate of SOC decomposition, provided soil erosion losses are negligible. SOC decomposition by microbial and soil fauna activity is influenced by temperature, moisture and soil organic matter quantity and quality (e.g. C : N ratio), which all interact to determine the decomposition rate (Sollins *et al.* 1996; Feller and Beare 1997). To increase SOC stocks, more C from vegetation needs to be added to the soil without a matching increase in decomposition rate. Alternatively, if less vegetation C is added to the soil (e.g. by vegetation being grazed or harvested) and decomposition rates remain the same, SOC stocks will decline. Management actions such as decreasing livestock stocking rates increase the forage biomass available to enter the soil, however, managing decomposition rates is much more problematic and difficult to achieve (Hassink 1994).

The reviewed studies indicate that land condition, specifically the abundance of perennial grass tussocks, tree cover, pasture biomass and ground cover, should influence SOC stocks for a given soil type and climate. However, the responses across the studies cited are often variable, resulting in high uncertainty. Nonetheless, these studies provide the current scientific understanding of the relationship between SOC stocks and land condition indicators in northern Australia's extensive grazing land and provide the basis for testing the generally accepted theory that: 'Good' land condition leads to higher SOC stocks and 'Poor' land condition leads to lower SOC stocks.

In this paper, we attempt to reduce the uncertainty associated with predicting change in SOC stocks by testing the relationships between land condition indicators and measurements of SOC stock. The goal was to identify important indicators that correlate with SOC stocks at both the core/quadrat scale and the plot/paddock scale. To do this, we used data from a paired-site sampling experiment to evaluate relationships, and then compared the findings with a collated dataset of 329 sites from across northern Australia to test for broad-scale applicability.

Methods

The focus region of this study was the land used for extensive grazing in Queensland and the Northern Territory (Fig. 2). Covering a large proportion of northern Australia, the region has a wide range of rainfall, soil type and vegetation type (grasslands, woodlands and forests) with much of the woodlands and forests in central and southern Queensland cleared for pasture improvement and grazing livestock (Gleeson *et al.* 2012). The Kimberley and Pilbara regions of northern Western Australia were not considered in this study due to a lack of available and suitable SOC and land condition data.

Paired-site sampling experiment

A paired-site sampling experiment conducted in the Northern Gulf and northern Burdekin regions of north Queensland was used to test the hypotheses that: 'Good' land condition leads to higher SOC stocks and 'Poor' land condition leads to lower SOC stocks. SOC stock was assessed on land in 'Good' versus 'Poor' land condition on five regionally important grazing land types (Fig. 2; Table 2) as part of the 'Keys for Healthy Savanna Lands' project in collaboration with the Northern Gulf Resource Management Group (Bray *et al.* 2010). Potential sites were identified in consultation with field extension officers with local knowledge regarding landholders that may have suitable study sites and would be willing to collaborate. Sites were selected based on the presence of an area in 'Good' land condition (predominantly land condition class A or B) and an adjacent area in 'Poor' land condition (predominantly land condition class C) to form a matching pair. Paired sites had similar land type, landscape position, tree cover and soil type and were generally

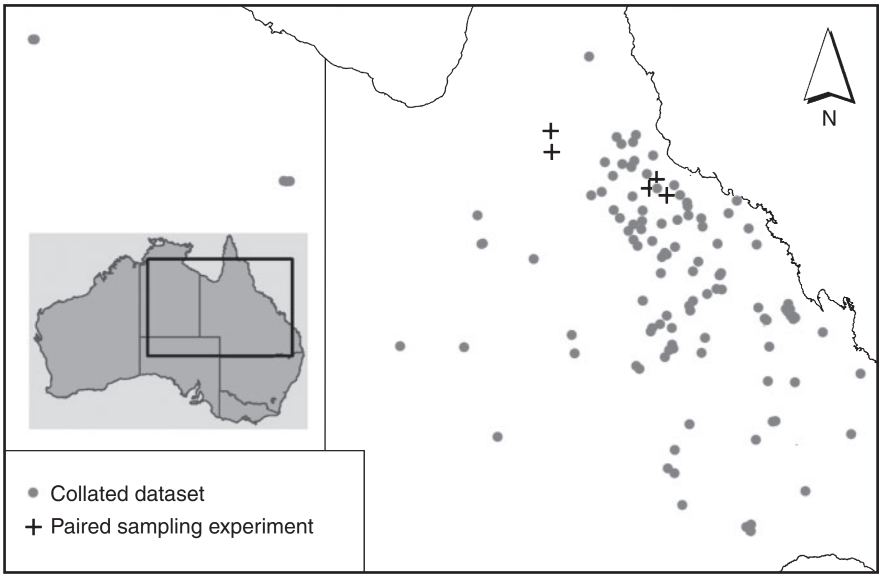

Fig. 2. Map of study region with sites.

located within 200 m of each other and typically separated by a fence.

Soil sampling and description

Twenty-five soil cores were extracted from each of the 10 1-ha plots on a 5×5 grid (25 m between cores) to avoid sampling bias. Intact soil cores to a depth of 0.5 m were extracted using a vehicle mounted hydraulic push-tube of ~50 mm diameter. The resulting soil sample was divided into depth increments that allowed calculation of total SOC in the 0–0.1- and 0–0.3-m layers. The soil samples for each core and depth layer were bagged separately and used for both SOC analysis and bulk density (Harms and Dalal 2003). One representative soil core up to 1.5 m depth for each site was used to describe the soil profile following the guidelines and terminology of the National Committee on Soil and Terrain (NCST 2009). The representative soil profile at each field site was classified according to the Australian Soil Classification (Isbell 2002), with the resulting soil class being referred to as the 'soil type' in all analysis and discussion.

Soil sample processing and analyses

Soil samples were processed using the method of Harms and Dalal (2003). Each soil sample was dried at 40°C until a constant weight was reached. A subsample was dried at 105°C until constant weight was reached for bulk density calculation. Soils were processed before laboratory C analysis by removing roots and crushing the soil to pass through a 2-mm sieve followed by grinding a subsample to <0.5 mm.

Total SOC was determined using the high temperature combustion method (Rayment and Lyons 2011). This included a pre-treatment to remove carbonates where present using H_2SO_3 acid. The SOC stock calculation was based on the bulk density of the sample, percentage of fine soil and SOC concentration in each soil layer. SOC stock values were expressed as $\mathrm{t\,C\,ha^{-1}}$ for a specific depth interval. The 0–0.1- and 0–0.3-m SOC stock value was the sum of the SOC in the layers that made up that depth interval. SOC stocks at each paired site were calculated on equivalent soil mass basis to remove the effect of bulk density on SOC stocks.

Vegetation and land condition assessment

Vegetation and land condition indicators recorded at the sites included:

- Perennial grass basal area (%),
- Distance to nearest perennial grass tussock (cm),
- Tree basal area (live) ($\mathrm{m^2\,ha^{-1}}$ at 1.3 m),
- Distance to tree and shrub canopy,
- Total ground cover (%),
- Forage and litter biomass ($\mathrm{t\,C\,ha^{-1}}$), and
- Land condition (ABCD framework).

Perennial grass basal area was measured at the paddock scale using a point frame to assess 500 points per site (Orr *et al*. 1991). Distance from the soil core to the nearest perennial grass tussock was measured using a tape measure, with a tussock being defined as being greater than 30 mm diameter and located within 1 m of the soil core. Wiregrasses (*Aristida* spp.) were regarded as perennial tussocks for this attribute but were not regarded as desirable perennial grasses in the ABCD land condition assessment due to their low palatability. On sites with few or no perennial grass tussocks but with the generally less desirable, exotic Indian bluegrass (*Bothriochloa pertusa*) present, distance to an Indian bluegrass 'tussock' or clump was measured.

Total ground cover (ground vegetation and litter) was visually estimated in the 0.5×0.5-m quadrat surrounding each core (DPI&F 2004) and the forage and litter within the quadrat harvested, dried at 60°C and weighed to calculate biomass. Forage and litter biomass was assumed to be 50% C. ABCD land condition was assessed within the quadrat surrounding the soil core location using the method of Fraser (2013). Land condition classification at the quadrat scale was similar to Stocktake (DPI&F 2004) but did not take into account woodland condition (Table 1).

Tree basal area was assessed at each soil core location using the Bitterlich method (Bitterlich 1948) and a relaskop instrument or dendrometer (1.3 m height). Distance from the soil core to the edge of the nearest tree or *Carissa* spp. shrub canopy was assessed using a category scale (Table 3).

Collated SOC dataset

SOC datasets from Queensland and Northern Territory grazing land, which had both total SOC stock and associated land condition indicator data at the core/quadrat or plot/paddock scale were collated ($n = 329$ sites; Table 4). Individual soil core data were used for values at the core/quadrat scale or averaged to generate plot/paddock-scale data. The majority of the datasets were collected for projects in which the authors of this paper were involved. The methods used for SOC and land condition indicators were the same as those used for the paired-site sampling experiment or used recognised techniques as appraised by the authors. Key criterion used for determining suitability of SOC stock data were: soil C concentration derived using the high temperature combustion method, appropriate soil depth intervals, soil bulk density taken into account and soil type could be determined. The key criterion for determining the applicability of land condition indicator data, if different from the paired-site sampling experiment methods, was that a recognised reliable method had been used. For example, TRAPS

Table 2. Land types and soil types at the paired-site sampling experimental sites

Land type site name	Soil type[A]
Red Basalt	Red Ferrosol
Black Basalt	Grey Vertosol
Goldfields	Red Chromosol
Granite	Bleached-Orthic Tenosol
Alluvial	Brown Kandosol

[A]The soil types are classes of the Australian Soil Classification (Isbell 2002).

Table 3. Categories for distance to tree and shrub canopy

Category	Tree canopy	Shrub canopy
1	Under canopy	Under canopy
2	<2 m away	<1 m away
3	2–5 m away (trees >5 m high)	>1 m away
4	>5 m away (trees >5 m high)	–

Table 4. List of soil carbon datasets and attributes

Project details	Location	Site no.	Reference
Paired-site sampling experiment Keys to healthy Savanna lands – 5 land types	North Queensland: Northern Gulf and Northern Burdekin region	10	Bray *et al*. (2010)
Toorak grazing trial	Western Queensland: Mitchell Grass land type	6	Orr and Phelps (2013); Pringle *et al*. (2014)
Mitchell grass and Channel country exclosures and paddock – 6 properties	Western Queensland: Mitchell grass and Channel country	12	Allen *et al*. (2013); David Phelps and David Cobon, pers. comm.
Burdekin exclosures and paddock – 3 properties	North Queensland: Burdekin region	6	Allen *et al*. (2013)
Grazing Systems Project sites – 8 properties	Southern, Central and North Queensland	56	Hall *et al*. (2011); Allen *et al*. (2013)
Wambiana grazing trial 2008 sampling	North Queensland: Burdekin region	2	O'Reagain *et al*. (2009); Segoli *et al*. (2014); Segoli *et al*. (2015)
Wambiana grazing trial 2009 sampling	North Queensland: Burdekin region	6	O'Reagain *et al*. (2009); Pringle *et al*. (2011)
Wambiana grazing trial 2010 sampling	North Queensland: Burdekin region	20	O'Reagain *et al*. (2009); Allen *et al*. (2013)
Climate Clever Beef – Clarke Creek	Central Queensland	26	http://futurebeef.com.au/wp-content/uploads/Soil-factsheet_web.pdf
Climate Clever Beef – Duaringa	Central Queensland: Box land type	6	Bray *et al*. (2015)
Climate Clever Beef – Rolleston	Central Queensland: Brigalow land type	3	Bray *et al*. (2015)
Climate Clever Beef – Barkly Tableland	Northern Territory: Barkly Tableland	11	Walsh and Shotton (2015)
Climate Clever Beef – Mt Carbine and Julia Creek	North Queensland	4	Joe Rolfe and Emma Hegarty, pers. com.; Bray *et al*. (2015);
NT Fire Experiment – Kidman Springs	Northern Territory: Victoria River District	34	Allen *et al*. (2014); Cowley *et al*. (2014)
Galloway Plains Grazing Trial	Central Queensland	10	Bray and Myles (2003); Orr *et al*. (2010*a*)
Burdekin thickening sites – 50 woodland sites	North Queensland: Burdekin region. One site in the Mitchell grass region	50	Krull and Bray (2005); Krull *et al*. (2005); Bray *et al*. (2006); Krull *et al*. (2007)
CRC Greenhouse Accounting – 5 woodland sites	Southern Queensland and Cape York	5	Dalal *et al*. (2005); Cape York sites not previously published
NCAS sites – 31 paired sites	Central and Southern Queensland	62	Harms and Dalal (2003); Harms *et al*. (2005)

woodland monitoring technique for tree basal area (Burrows *et al*. 2002), percentage distance intersected for grass basal area (Hall *et al*. 2011), ground cover and land condition derived from photos (Karfs *et al*. 2009*b*) and BOTANAL visual estimation of pasture biomass (Tothill *et al*. 1992).

The climate variables of annual average daily temperature, rainfall and vapour pressure (VP) were extracted for each site using the SILO interpolated gridded climate database for 1889 until 2014 (Jeffrey *et al*. 2001; DSITI 2016).

Statistical analyses

Paired-site sampling experiment

The appropriateness of the 'Good' and 'Poor' land condition classifications were evaluated by comparing the percentage of quadrats with land condition classes 'A and B' and those with classes 'C and D' using a chi-square test for contingency tables. Pasture, litter and total biomass (t C ha^{-1}), distance to nearest perennial grass tussock (cm), total ground cover (%) and SOC stocks in the 0–0.1- and 0–0.3-m layers (t C ha^{-1}) for both 'Good' and 'Poor' land condition plots were compared using ANOVA with treatment (Good/Poor land condition) as a fixed effect and site, transect within site and quadrat within transect as random effects. To stabilise variances, biomass measures and distance to perennial grass were square-root transformed, total ground cover was arcsine-transformed and SOC stocks were log-transformed before analysis. The between-plot residual was then compared with the within-plot variation to assess the random site by treatment interaction.

Relationships between SOC stocks (log-transformed) and the continuous land condition indicators (biomass, distance to perennial grass and total ground cover) were investigated using linear regression analysis for each land type. Relationships between SOC stocks and the categorical indicators (land condition class and tree canopy) were investigated through modelling with the restricted maximum likelihood approach.

Collated SOC dataset

SOC stocks were calculated at two scales: (1) a 'paddock' scale, where land condition indicator measurements were made across the paddock, and matched with a single 'paddock' SOC stock value (average of multiple soil samples via sample bulking) and (2) a 'quadrat' scale where all land condition indicator measurements were made within a quadrat surrounding an individual soil core providing a unique 'SOC – land condition indicator measurement' pair. For statistical analysis the paddock and quadrat data were considered separately. The paddock dataset consisted of 310 and 284 observations, and the quadrat dataset consisted of 1037 and 961 observations for the 0–0.1- and 0–0.3-m soil depth layers, respectively.

The response variables of SOC stock in the 0–0.1- and 0–0.3-m layers were log-transformed to stabilise variances. Categorical variables of soil type (Soil), land condition class (LC), distance class to the canopy of the nearest tree (Tree_canopy) and *Carissa* spp. shrub (Carissa_canopy) were included as explanatory variables. The soil types of Rudosol, Ferrosol, Tenosol and Hydrosol were excluded from the 'paddock'-scale dataset due to limited data availability. Tree_canopy and Carissa_canopy were used only with the 'quadrat'-scale data. The following climate and land condition indicator variables were included as continuous explanatory variables: average annual temperature (Temp), average annual rainfall (Rain) and average annual VP, live tree basal area (TBA_live), ground cover (Cover%), distance to perennial tussock (Per_dist), perennial grass basal area (BA%_Per), pasture biomass (P_biom) and litter biomass (L_biom).

We used an adaptation of the statistical methodology employed by Allen *et al*. (2013) as follows. For each of the response variables at both the quadrat and paddock scales, random forest regression (Breiman 2001) was used to identify the subset of explanatory variables that had the greatest effect on SOC stock variability. Explanatory variables were then ranked on their resulting random forest importance with the algorithm run 20 times to obtain a robust ranking. Using this approach, the climate variables were identified as the dominant influence on variability.

A cubic regression spline was applied to the three climate variables (identified by '*' in Table 5) resulting in residuals de-trended of climate effects. These residuals were then subjected to multiple linear regression with the explanatory variables identified as important by the random forest (identified by '#' in Table 5). Models included the selected continuous variables and their interaction with soil type. A stepwise procedure was used to eliminate non-significant ($P > 0.05$) terms from the model. Note that when fitting the regressions, observations were restricted to those with data available across all explanatory variables used in the initial model (i.e. those selected from the random forest regression), regardless of whether it was included in the final model or not. This resulted in the paddock dataset being reduced to 163 observations for both the 0–0.1- and 0–0.3-m soil layers, and the quadrat dataset to 861 observations.

Results

Paired-site sampling experiment

There was a significant difference ($P < 0.001$) in ABCD land condition classification for the 'Good' and 'Poor' paired sites,

Table 5. Explanatory variables ranked on random forest importance at the paddock and quadrat scale for each soil depth layer

The variables are annual average temperature (Temp), annual average rainfall (Rain) and annual average vapour pressure (VP), live tree basal area (TBA_live), ground cover (Cover%), distance to perennial tussock (Per_dist), perennial grass basal area (BA%_Per), pasture biomass (P_biom), litter biomass (L_biom), soil type (Soil), land condition class (LC), distance class to the canopy of the nearest tree (Tree_canopy) and *Carissa* spp. shrub (Carissa_canopy)

Variable	Importance	Variable	Importance
0–0.1 m soil layer paddock scale		*0–0.3 m soil layer paddock scale*	
Temp *	29.8	Temp *	27.1
Rain *	22.4	Rain *	16.7
VP *	11.3	VP *	11.9
Soil #	10.3	Soil #	11.9
Cover% #	9.1	P_biom #	10.6
P_biom #	7.5	Cover% #	8.4
TBA_live #	6.0	Per_dist #	6.8
Per_dist #	3.5	TBA_live #	6.6
LC	2.6	L_biom	1.8
L_biom	1.4	LC	1.8
BA%_Per	0.3	BA%_Per	0.4
0–0.1 m soil layer quadrat scale		*0–0.3 m soil layer quadrat scale*	
Temp *	24.1	Soil #	28.5
Soil #	18.0	Temp *	11.8
Rain *	13.2	VP *	11.0
VP *	8.9	Rain *	10.3
Cover% #	7.6	Cover% #	7.2
P_biom #	7.3	TBA_live #	7.1
TBA_live #	6.5	P_biom #	6.8
Per_dist #	5.8	Per_dist #	5.4
LC	2.6	BA%_Per	3.6
L_biom	2.1	L_biom	2.9
Tree_canopy	2.0	LC	2.6
BA%_Per	1.5	Tree_canopy	2.1
Carissa_canopy	0.6	Carissa_canopy	1.2

*Variables of primary importance used in cubic regression spline.
#Variables of secondary importance used in regression of residuals.

with 78% of the 'Good' site quadrats in A/B condition and 77% of the 'Poor' site quadrats in C/D condition, thus confirming the correct classification of sites.

Pasture, litter and total biomass were higher ($P < 0.05$) on sites classified as 'Good' compared with those classified as 'Poor'. The significant ($P < 0.001$) site by treatment interaction for pasture biomass suggests the treatment effect differs with site, whereas for litter and total biomass the interaction was not significant ($P > 0.10$). The distance to the nearest perennial tussock did not differ ($P > 0.10$) between 'Good' and 'Poor' land condition sites, although there was evidence ($P < 0.001$) that this effect varied among sites. Distance to perennial tussock was less on 'Good' than 'Poor' for all sites except the Red Basalt site where there was no significant difference. This was likely to have been due to the dense tussocks of the exotic grass *B. pertusa* on the 'Poor' site. Ground cover was higher ($P < 0.05$) on 'Good' than 'Poor' land condition sites (81% vs 53%) but there was evidence ($P < 0.001$) that this effect differed with site, with less difference for the Goldfields and Red Basalt sites.

There was no significant difference ($P > 0.10$) in the average SOC stocks between 'Good' and 'Poor' land condition sites in either the 0–0.1-m soil layer (9.9 and 9.1 t C ha^{-1}, respectively), or the 0–0.3-m layer (23.3 and 21.9 t C ha^{-1}, respectively), but there was evidence ($P < 0.01$) that the effect varied among land types (Fig. 3).

Relationships between SOC stocks and distance to perennial tussock, pasture and total biomass, and ground cover differed with land type. The relationship between distance to nearest perennial tussock and SOC stocks differed among land types in both rate (slope) and magnitude (intercept) and explained 69% and 75% of variation in SOC in the 0–0.1- and 0–0.3-m layers, respectively (Fig. 4). SOC stocks decreased with increasing distance to the nearest tussock at the Black Basalt site whereas there was no relationship (slope not different from zero) or a weak positive relationship at the other sites (Fig. 4),

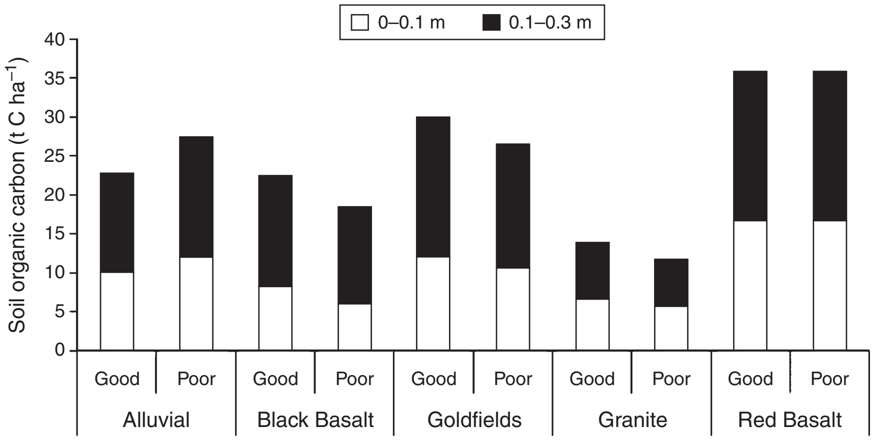

Fig. 3. Soil organic carbon stocks in the paired-site sampling experiment for sites classified in 'Good' and 'Poor' classification for the 0–0.1- and 0–0.3-m layer.

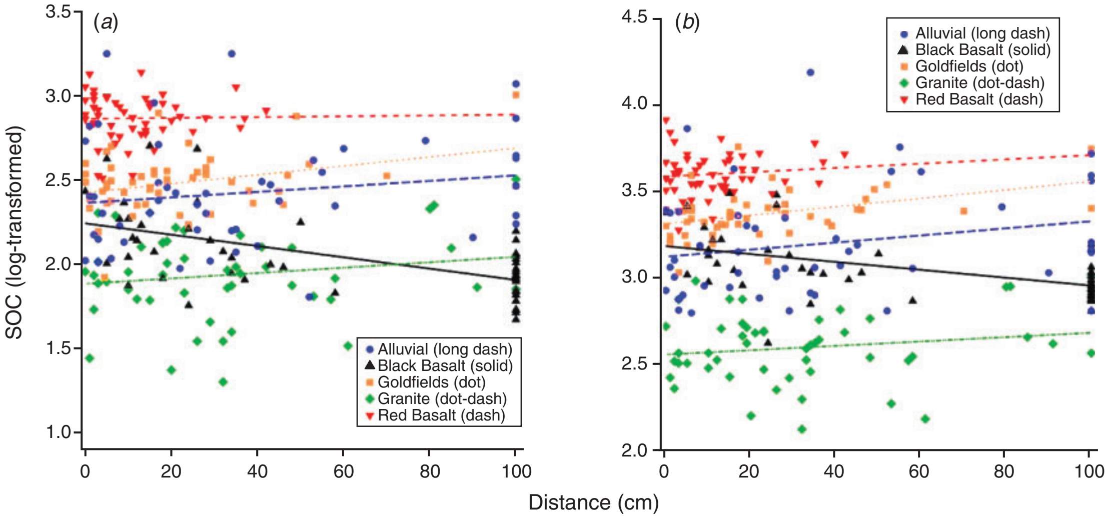

Fig. 4. Relationship between distance to perennial tussock and soil organic carbon stock in the (*a*) 0–0.1-m layer and the (*b*) 0–0.3-m layer for the paired-site sampling experiment.

contrasting with theory as depicted in Fig. 1. In both the 0–0.1- and 0–0.3-m layers, SOC stocks increased with increasing pasture biomass at similar rates among sites but differed in magnitude, being least for Granite and greatest for Red Basalt ($R^2 = 67\%$ and 74%, respectively). Similar results were observed for total biomass but with the relationship among sites differing in both rate and magnitude. There was no relationship between ground cover and SOC stocks for the Alluvial and Red Basalt sites whereas SOC stocks increased with increasing ground cover at the Goldfields, Granite and Black Basalt sites in each of the 0–0.1- and 0–0.3-m soil layers ($R^2 = 70\%$ and 76%, respectively).

Log-transformed SOC stocks in the 0–0.1-m layer tended ($P = 0.055$) to be lower for land condition class D than for classes A and B (8.2 vs 10.0 and 9.7 t C ha^{-1}, respectively). There was no significant difference ($P > 0.10$) in SOC stocks between land condition classes in the 0–0.3-m layer. Similarly, SOC stocks in the 0–0.1-m layer differed ($P < 0.001$) between tree canopy ratings with more C under the canopy (11.3 t C ha^{-1}) than away from the canopy (9.7, 9.3 and 9.0 t C ha^{-1}) whereas there was no difference in the 0–0.3-m layer. These results suggest that SOC stock in the 0–0.1-m layer may be more important when comparing response to land condition indicators.

Collated dataset

Explanatory power of land condition indicators

The three climate variables of annual average rainfall, temperature and VP (identified by '*' in Table 5) were identified as the dominant influence on variability in SOC stock. The explanatory variables of soil type, ground cover, pasture biomass, tree basal area and distance to perennial tussock were considered of secondary importance (identified by '#' in Table 5). ABCD land condition and perennial grass basal area did not provide substantial explanatory power.

Paddock scale

Climate variables explained 62.6% and 57.5% of the variation in paddock-scale SOC stocks in the 0–0.1- and 0–0.3-m layers, respectively, thus confirming that climate is a major driver of SOC stocks. There was a negative response to annual average temperature and a positive response to VP, and for the 0–0.1-m layer, also a positive response to rainfall.

After removing the climate influence, 36% and 32% of the variation in the SOC stock residuals in the 0–0.1- and 0–0.3-m layers, respectively, was explained by a regression model of Soil + TBA_live + Soil.TBA_live. Combining the climate effects and regression model, a total of 76% and 71% of SOC variation was explained in the 0–0.1- and 0–0.3-m layers, respectively. For the Kandosol and Sodosol soil types, tree basal area was positively related to SOC stock in both the 0–0.1- and 0–0.3-m layers whereas for the Vertosol soil type, tree basal area tended to be negatively related to SOC stock, but only in the 0–0.1-m layer. There were no significant linear relationships for the other soil types.

Quadrat scale

At the quadrat scale, climate variables explained 52% and 32% of the variation in SOC stocks for the 0–0.1- and 0–0.3-m layers, respectively. Similar to the paddock scale, there was a negative response to annual average temperature and a positive response to VP, and for the 0–0.1-m layer, there was also a positive response to rainfall.

After removing the climate effects, 40% and 42% of the variation in the SOC stock residuals for the 0–0.1- and 0–0.3-m layers, respectively, was explained by the regression models. Combining the climate effects and regression model, a total of 71% and 63% of SOC variation was explained for the 0–0.1- and 0–0.3-m layers, respectively. In contrast to the paddock-scale models, the quadrat-scale regression models included terms for distance to perennial tussock and cover, and also pasture biomass for the 0–0.1-m layer. The explanatory variables in the regression model for SOC residuals in the 0–0.1-m layer were: Per_dist, TBA_live, Cover%, P_biom, Soil, P_biom × Soil and Cover% × Soil. The explanatory variables in the regression model for SOC residuals in the 0–0.3-m layer were: Cover%, Per_dist, TBA_live, Soil and Cover% × Soil.

Distance to perennial tussock showed a positive relationship with SOC stock residuals for both the 0–0.1- and 0–0.3-m layers and no significant interaction with soil type. This was similar to four of the five land types in the paired-site sampling experiment which had a weak positive relationship, although the other site had a negative relationship (Fig. 4). Tree basal area showed a positive relationship with SOC stock residuals for both the 0–0.1- and 0–0.3-m layers and no significant interaction with soil type. The relationship between ground cover and SOC stock residuals in the 0–0.1-m layer interacted with soil type, being positive for Sodosol, Tenosol and Calcarosol and slightly negative for Vertosol. The relationship between pasture biomass and SOC stock residuals in the 0–0.1-m layer also interacted with soil type, the only soil type with a positive relationship being Vertosol. The interaction between ground cover and soil type for the 0–0.3-m layer was due to positive relationships for Calcarosol, Sodosol and Tenosol soil types and negative relationships for Ferrosol, Kandosol and Vertosol, which differed from the 0–0.1-m layer where Kandosol and Ferrosol had no relationship.

Discussion

Understanding the environmental and management drivers and/or associated land condition indicators on the variation in SOC stocks in extensive grazing land is important as it may lead to C accounting methodologies that significantly impact Australia's greenhouse gas position. In addition, grazing businesses may be able to generate additional 'C' income by utilising the Australian Government's Emissions Reduction Fund.

Climate and soil type

As expected from numerous studies reported in the literature, climate variables proved to be the dominant driver of SOC stock variability in this study, with a positive relationship with annual average rainfall and VP, and a negative relationship with temperature. Soil type was also an important explanatory term. Soil type and climate are outside the influence of grazing management but are likely to provide substantial constraints on the magnitude of SOC stock change. Year-to-year climate variability is likely to have little impact on total SOC in grazing land (Segoli *et al*. 2015), but longer-term climate change may impact SOC stocks and stability due to effects on biomass production (Parton *et al*. 1995).

Grazing land management and SOC stock

The effects of grazing land management in terms of land condition and livestock productivity are generally well understood (McIvor *et al*. 1995*a*; Quirk and McIvor 2007; Orr and Phelps 2013; Hunt *et al*. 2014). However, the relationship between grazing land management activities and SOC stocks is less apparent.

Grazing management strategies including, varying stocking rates, rotational grazing, removal of livestock and sowing alternate forage species (e.g. legumes or high biomass producing species), impacts on pasture biomass, ground cover, pasture species composition and vegetation quality. Research indicates that the response of SOC stocks to 'improved' grazing management has been inconsistent, with negative, positive and negligible responses found, and these effects are often confounded by interactions with land type (Holt 1997; Pringle *et al*. 2011, 2014; Allen *et al*. 2013; McSherry and Ritchie 2013; Pringle *et al*. 2014; Sanderman *et al*. 2015). This may in part be due to different management activities resulting in the same land condition, for example, continuous grazing and rotational grazing (Hall *et al*. 2011; Sanderman *et al*. 2015). Protection of pasture from grazing has also demonstrated variable results with similar or higher SOC stocks when compared with grazed pasture (Bird *et al*. 2000; Carter and Fraser 2009; Witt *et al*. 2011; Allen *et al*. 2013; Pringle *et al*. 2014; Walsh and Shotton 2015).

Varying the abundance and distribution of woody plants through tree clearing for pasture improvement or by encouraging tree regrowth for vegetation C sequestration or other environmental reasons might also be expected to impact SOC stocks. However, numerous studies report little or no detrimental impact of these practices on SOC stocks (Guo and Gifford 2002; Dalal *et al*. 2005; Harms *et al*. 2005; Marin-Spiotta *et al*. 2009; Fujisaki *et al*. 2015).

Manipulating the frequency, intensity and timing of fires influences soil nutrient availability and the composition of forage and woody plants (Cook 1994; Orr *et al*. 1997; Crowley *et al*. 2009; Cowley *et al*. 2014). However, fire management in grazing land appears to have little consistent or clear impact on SOC stocks, although some studies have found evidence that long unburnt areas have higher SOC compared with burnt areas (Bird *et al*. 2000; Fynn *et al*. 2003; Allen *et al*. 2014).

Land condition indicators and SOC stock

Given the inconsistent evidence of the impact of broad grazing land management practices on SOC stocks, we hypothesised that land condition might be an appropriate surrogate for detecting SOC change. In the paired-site sampling experiment, the following land condition indicators demonstrated significant relationships with SOC stocks: distance to perennial tussock, pasture and total biomass, ground cover, land condition class and tree canopy class. Tree basal area also demonstrated explanatory power in the collated dataset. These relationships and the implications for SOC stocks and management are discussed below.

Perennial grass

The perennial grass land condition indicators, distance to nearest perennial grass tussock and perennial grass basal area, were expected, respectively, to have a strong negative and a strong positive relationship with SOC stocks, as depicted in Fig. 1 (Northup *et al*. 1999, 2005; Ash *et al*. 2001). However, the paired-site sampling experiment demonstrated a weak positive relationship between SOC stock and distance to perennial tussock for four of the five land types sampled (Fig. 4). This finding was supported by the collated dataset where a positive relationship was also found. Distance to perennial tussock was an explanatory term included in the regression model for the quadrat-scale collated data. These findings suggest that perennial grasses are an important factor in determining SOC stock, although not as strong or consistent or necessarily in the same direction as depicted in Fig. 1. A recent study from grazing land in western New South Wales also found that perennial grass patches had the highest SOC stocks for the 0–0.1- and 0–0.3-m soil layers, but they were not significantly different from patches classified as 'Bare' or 'Annual' (Waters *et al*. 2015). A possible explanation for this is that in many land types, substantial amounts of ephemeral (short-lived) grasses and forbs grow between the perennial grass tussocks, possibly masking the strong contours of SOC concentration that are depicted in Fig. 1. For example, the 'Good' condition Granite site in the paired-site sampling experiment had a perennial grass basal area of 3.6% and an ephemeral basal area of 5.6%. Additionally, although perennial grass tussocks are often long-lived (Orr and Phelps 2013), when they do eventually die, the area of high SOC stock would remain for many years due to the slow turnover of SOC (Krull *et al*. 2005), which could confound the results when measuring distance to the nearest 'live' perennial grass tussock.

The concept of '3P' grasses (perennial, productive and palatable) is a key parameter within the ABCD land condition framework. Sites in Good to Fair (A/B) condition will always have a substantially higher density of 3P grasses and a greater contribution of 3P grasses to pasture biomass, than Poor or Degraded (C/D) sites. However, sites with a low density of 3P grasses may still have a high density and biomass contribution from perennial grasses which are not palatable, such as *Aristida* spp. or less desirable species, such as *B. pertusa*. The distinction between 3P and non-3P grasses was not made across datasets within this study. However, it seems likely that any perennial grass with high biomass will make a strong contribution to SOC stocks regardless of its palatability. The density of '3P' grasses, although a key parameter in assessing ABCD land condition and pastoral productivity may thus be a poor indicator of SOC stocks when considered in isolation.

Tree cover

SOC stocks in the paired-site sampling experiment were 16–25% higher directly under the tree canopy in the 0–0.1-m layer compared with areas away from the tree canopy. This supports similar findings in grazing land in western New South Wales (Waters *et al*. 2015). However, at the paddock scale, the area of tree canopy is relatively small (average of 10% in the paired-site sampling experiment) meaning the impact on SOC stocks may be relatively small unless higher tree densities are achieved.

Conversely, when tree canopy cover is high, pasture biomass will decline (Scanlan 2002), negatively influencing SOC stock. In the collated dataset, tree basal area was the primary land condition indicator in the regression model at the paddock scale and was an explanatory term at the quadrat scale for both soil depth layers. At the paddock scale there was an interaction between tree basal area and soil type with increases in SOC being associated with Kandosols and Sodosols and a negative relationship with Vertosols in the 0–0.1-m layer. The reason for this interaction is unclear, but may be related to some of the Vertosol sites being cleared or naturally treeless.

Pasture biomass and ground cover

In northern Australia's grazing land there is a positive relationship between pasture biomass and ground cover (Bartley *et al*. 2010; Fraser 2013). Increased pasture biomass and ground cover were positively correlated with SOC stock for the paired-site sampling experiment. Pasture biomass and ground cover at any point in time will be impacted by recent grazing and fire. However, in general, higher pasture biomass and ground cover mean more perennial grasses (McIvor and Gardener 1995) and higher leaf area and therefore more net primary productivity that increases C inputs into the soil, potentially leading to higher SOC stocks. In the collated dataset, ground cover and its interaction with soil type were explanatory terms in the quadrat-scale regression for both soil depth layers. The Calcarosol, Sodosol and Tenosol soil types had positive relationships between SOC stocks and ground cover, whereas Vertosols had a negative relationship. Further, pasture biomass and its interaction with soil type were also explanatory terms in the quadrat-scale regression, but only for the 0–0.1-m layer, with the Vertosol soil type having a positive relationship with SOC stock. No explanation is apparent for the lack of a positive relationship for the other soil types to pasture biomass and the different response between the pasture biomass and ground cover land condition indicators.

Managing grazing land for higher pasture biomass and increased ground cover would contribute to reducing the grazing industry's potentially adverse environmental impacts. From a greenhouse gas balance perspective, high average pasture biomass would store more C from the atmosphere than low average pasture biomass (Bray *et al*. 2014; Whish *et al*. 2016). This is potentially significant when considered across the 207 million ha of grazing land in northern Australia. Additional co-benefits of managing grazing land for higher pasture biomass and ground cover would be through enhanced rainfall infiltration and reduced sediment loss (Bartley *et al*. 2014; Fraser and Stone 2016) as well as increased productivity, profitability and reduced drought risk (Scanlan *et al*. 2013; Hunt *et al*. 2014; O'Reagain *et al*. 2014; Walsh and Cowley 2016).

Land condition class

The ABCD land condition classification is based on pasture, soil and woodland condition parameters and is inherently an indicator of net primary productivity. More pasture biomass is expected to be grown when land is in good condition, thus contributing to enhanced grazing productivity (Table 1; McIvor *et al*. 1995*a*). We had anticipated that this would translate to a higher input to SOC and higher SOC stock. In the paired-site sampling experiment there was 17% less ($P = 0.055$) SOC stock in the 0–0.1-m layer for land in very poor D condition compared with A/B land condition. Fraser and Stone (2016) found a similar relationship in the 0–0.05-m soil layer for SOC concentration in grazed plots with greater than 60% sand content, but this relationship was not apparent when SOC stocks were subsequently calculated. Using a land condition class system based on three classes, Ash *et al*. (1995) found a much stronger impact on SOC concentration with a >40% decline between pastures in good and poor condition.

In the collated dataset, we found that land condition class was not a significant explanatory variable for SOC stocks in either soil depth layer or the two scales assessed. This may be related to the fact that the ABCD land condition framework focuses on the presence of 3P grasses, while underestimating the potential contribution to SOC stocks of unpalatable perennial grasses and ephemeral species, as discussed above. It may also be related to the propensity for low 3P grass density under high tree and shrub canopy cover. In addition, the pastorally focussed ABCD land condition framework would have a lower land condition rating when tree and shrub cover was higher than considered desirable. Current SOC stocks may also be influenced by long-term site history, with finer C fractions persisting for millennia, and hence potentially decoupled from the current land condition of a site. In addition, where soils are in poor condition, have poor rainfall infiltration or have been eroded and lost nutrients, soil microbial activity may be reduced thereby slowing the rate of SOC loss (Sollins *et al*. 1996; Pringle *et al*. 2014).

Implications for SOC sequestration

1. Interactions between soil type and land condition indicators were common

Interactions with soil type were found for tree basal area, distance to perennial tussock, pasture biomass and ground cover. Soil type interactions have also been found for specific management activities (Pringle *et al*. 2011; Allen *et al*. 2013). Fraser (2013) classified sites on texture classes in an attempt to avoid soil type interactions. The interaction with soil type means that management activities or objectives to change land condition indicators to increase SOC stocks, need to carefully account for soil type and cannot be applied generally across a paddock, property or region.

2. Surface soil layers were more responsive to land condition variation than deeper soil layers

The surface 0–0.1-m layer was more likely to have a significant difference in SOC stocks in response to varying land condition, particularly as indicated by pasture biomass and distance to perennial tussock. This is probably due to the shorter mean residence times for C in this layer reflecting more recent land condition change (Krull *et al*. 2005). Sampling strategies for verifying SOC change as part of a sequestration project should focus on the surface soil layer, with the deeper soil layers possibly sampled less regularly, reducing sampling costs.

3. SOC stocks were more closely correlated with certain land condition indicators

Tree basal area, tree canopy cover, ground cover, pasture biomass and distance to perennial tussock were the most explanatory land condition indicators of SOC stocks across datasets and analysis scales. In combination with soil type, these land condition indicators accounted for up to 42% of the variation in the residuals after climate was removed. SOC stock sampling and monitoring strategies may benefit from including these indicators to reduce the cost of monitoring by providing evidence on the likely direction of SOC change between SOC sampling events.

4. The risk of incorrectly predicting the direction of change in SOC stocks was high

Despite identifying trends between land condition indicators and SOC stock for different datasets, analysis scales and soil depth layers, we found that the response of different land condition indicators often varied between soil types. For example, distance to perennial tussock had a strong negative relationship for one soil type in the paired-site sampling experiment, contrasting with a negligible or a weak positive relationship for the other soil types. In addition, the interaction of soil type with tree basal area, ground cover and pasture biomass adds to the complexity, creating high uncertainty when assessing the potential benefits of a C sequestration project for any particular location.

5. Management for SOC sequestration is complementary to other environmental and productivity goals

Grazing management to improve or maintain land condition and higher average pasture biomass and ground cover has been shown to improve herd profitability and per head productivity (Burrows *et al*. 2010; Orr *et al*. 2010*b*; O'Reagain and Bushell 2013; Scanlan *et al*. 2013; Hunt *et al*. 2014; O'Reagain *et al*. 2014; Walsh and Cowley 2016) and lead to a reduction in potential adverse environmental impacts through maintaining higher C stocks in the pasture biomass, improved rainfall infiltration and reduced sediment loss (Bartley *et al*. 2014; Bray *et al*. 2014; Fraser and Stone 2016). However, increasing tree biomass for C sequestration is likely to have trade-offs with grazing productivity and profitability, which needs to be carefully assessed (Donaghy *et al*. 2010; Gowen and Bray 2016; Whish *et al*. 2016).

Conclusion

Relationship between SOC stocks and the condition of grazing land was examined at 329 sites across northern Australia, using a range of land condition indicators. We found significant relationships between certain land condition indicators and SOC stocks. However, the strength of these relationships was not consistent across all the datasets and at the different spatial scales used. In addition, interactions between soil type and land condition indicators complicate the interpretation of results. Based on this analysis, together with evidence from other published scientific studies, it is recommended that beef producers in northern Australia exercise caution when considering the implementation of SOC sequestration projects. There is a high risk of incorrectly predicting the direction and magnitude of SOC stock change based on land condition indicators and land management activities for a particular paddock or property.

Despite the uncertainty for generating income from SOC sequestration activities, focusing grazing management to improve land condition is likely to have the complementary benefits of improved productivity and profitability, as well as positive environmental effects.

Acknowledgements

This work was co-funded by the Queensland Department of Agriculture and Fisheries in partnership with a range of industry and Government funding providers. The work was undertaken in collaboration with other Qld and NT government agencies, natural resource management groups (particularly the Northern Gulf Resource Management Group) and CSIRO. Many individuals have been involved in the project design, sample collection and processing for the SOC samples over many years. Special mention of individuals not on the author list but contributing significantly to soil carbon projects include: Evelyn Krull, Bill Burrows, Jan Skjemstad, Mal Rutherford, Joe Rolfe, Bob Shepherd, Jim Payne, Angie Woods, John Bushnell, Anna Richards, Robyn Cowley, Natalie Baxter and Peter Shotton. A special thank you goes to the land managers who allowed access to their properties.

References

Allen, D. E., Pringle, M. J., Page, K. L., and Dalal, R. C. (2010). A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands. *The Rangeland Journal* **32**, 227–246. doi:10.1071/RJ09043

Allen, D. E., Pringle, M. J., Bray, S., Hall, T. J., O'Reagain, P. O., Phelps, D., Cobon, D. H., Bloesch, P. M., and Dalal, R. C. (2013). What determines soil organic carbon stocks in the grazing lands of north-eastern Australia? *Soil Research* **51**, 695–706. doi:10.1071/SR13041

Allen, D. E., Bloesch, P. M., Cowley, R. A., Orton, T. G., Payne, J. E., and Dalal, R. C. (2014). Impacts of fire on soil organic carbon stocks in a grazed semi-arid tropical Australian savanna: accounting for landscape variability. *The Rangeland Journal* **36**, 359–369. doi:10.1071/RJ14044

Ash, A. J., Howden, S. M., and McIvor, J. G. (1995). Improved rangeland management and its implications for carbon sequestration. *In*: 'Proceedings of the Fifth International Rangeland Congress'. Salt Lake City, UT, July 1995. (Ed. N. E. West.) pp. 19–20. (Society for Range Management: Denver, CO.)

Ash, A., Corfield, J., and Ksiksi, T. (2001). 'The Ecograze Project Developing Guidelines to Better Manage Grazing Country.' (CSIRO: Australia; Department of Primary Industries: Queensland.)

Australian Government (2014). Carbon Credits (Carbon Farming Initiative) (Sequestering carbon in soils in grazing systems) Methodology Determination 2014. ComLaw: Australian Government. Available at: www.comlaw.gov.au/Details/F2014L00987 (accessed 11 January 2016).

Bartley, R., Corfield, J. P., Abbott, B. N., Hawdon, A. A., Wilkinson, S. N., and Nelson, B. (2010). Impacts of improved grazing land management on sediment yields, Part 1: Hillslope processes. *Journal of Hydrology* **389**, 237–248. doi:10.1016/j.jhydrol.2010.05.002

Bartley, R., Corfield, J. P., Hawdon, A. A., Kinsey-Henderson, A. E., Abbott, B. N., Wilkinson, S. N., and Keen, R. J. (2014). Can changes to pasture management reduce runoff and sediment loss to the Great Barrier Reef? The results of a 10-year study in the Burdekin catchment, Australia. *The Rangeland Journal* **36**, 67–84. doi:10.1071/RJ13013

Beutel, T. S., Tindall, D., Denham, R., Trevithick, R., Scarth, P., Abbott, B., and Holloway, C. (2014). 'Getting ground cover right: thresholds and baselines for a healthier reef.' Report to the Reef Rescue Research and Development Program. p. 64. (Reef and Rainforest Research Centre Limited: Cairns, Qld.)

Bird, M. I., Veenendaal, E. M., Moyo, C., Lloyd, J., and Frost, P. (2000). Effect of fire and soil texture on soil carbon in a sub-humid savanna (Matopos, Zimbabwe). *Geoderma* **94**, 71–90. doi:10.1016/S0016-7061(99)00084-1

Bitterlich, W. (1948). Die Winkelzahlprobe. *Allgemeine Forst- und Holzwirtschaft Zeitung* **59**, 4–5.

Bray, S. G., and Myles, D. J. (2003). Future native pasture productivity has been compromised through sustained high stocking rates. *In*: 'VIIth International Rangelands Congress'. 2003, Durban, South Africa. (Eds N. Allsopp, A. R. Palmer, S. J. Milton, K. P. Kirkman, G. I. H. Kerley, C. R. Hurt and C. J. Brown.) pp. 855–857. (Society for Range Management: Denver, CO.)

Bray, S., and Willcocks, J. (2009). 'Net Carbon Position of the Queensland Beef Industry.' (Department of Employment, Economic Development and Innovation: Queensland.)

Bray, S. G., Krull, E. S., Harms, B. P., Baxter, N., Rutherford, M., Yee, M., and Cogle, L. (2006). 'Assessment of vegetation change in the Burdekin Catchment of Queensland – Project report QI06091.' (Department of Primary Industries and Fisheries: Queensland.)

Bray, S., Harms, B., Fraser, G., and Rutherford, M. (2010). Assessment of soil carbon stocks in response to land condition in Queensland's northern grazing land: Appendix A. *In*: 'Keys to Healthy Savanna Lands Final Report'. (Ed. K. Broad) pp. 21–47. (DEEDI: Kairi.)

Bray, S., Doran-Browne, N., and O'Reagain, P. (2014). Northern Australian pasture and beef systems. 1. Net carbon position. *Animal Production Science* **54**, 1988–1994.

Bray, S., Walsh, D., Rolfe, J., Broad, K., Cowley, R., Daniels, B., English, B., Ffoulkes, D., Gowen, R., Gunther, R., Hegarty, E., McGrath, T., Pahl, L., Shotton, P., and Whish, G. (2015). 'Northern grazing carbon farming – integrating production and greenhouse gas outcomes 1.' Climate Clever Beef Final Report. (Department of Agriculture and Fisheries: Rockhampton, Qld.)

Breiman, L. (2001). Random forests. *Machine Learning* **45**, 5–32. doi:10.1023/A:1010933404324

Bryan, B. A., Nolan, M., Harwood, T. D., Connor, J. D., Navarro-Garcia, J., King, D., Summers, D. M., Newth, D., Cai, Y., Grigg, N., Harman, I., Crossman, N. D., Grundy, M. J., Finnigan, J. J., Ferrier, S., Williams, K. J., Wilson, K. A., Law, E. A., and Hatfield-Dodds, S. (2014). Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Global Environmental Change* **28**, 166–181. doi:10.1016/j.gloenvcha.2014.06.013

Burrows, W. H., Henry, B. K., Back, P. V., Hoffmann, M. B., Tait, L. J., Anderson, E. R., Menke, N., Danaher, T., Carter, J. O., and McKeon, G. M. (2002). Growth and carbon stock change in eucalypt woodlands in northeast Australia: ecological and greenhouse sink implications. *Global Change Biology* **8**, 769–784. doi:10.1046/j.1365-2486.2002.00515.x

Burrows, W. H., Orr, D. M., Hendricksen, R. E., Rutherford, M. T., Myles, D. J., Back, P. V., and Gowen, R. (2010). Impacts of grazing management options on pasture and animal productivity in a *Heteropogon contortus* (black speargrass) pasture in central Queensland. 4. Animal production. *Animal Production Science* **50**, 284–292. doi:10.1071/AN09145

Carter, J. O., and Fraser, G. (2009). 0–5 cm soil carbon trends with removal of domestic stock: an analysis of data from 12 grazing exclosures. Appendix 2. RIRDC Report. *In*: 'Prognosis for Carbon Sequestration in Rangelands upon Destocking. A Case Study of the Vast Australian Rangelands with Reference to Biogeochemistry, Ecology, Fire, Biodiversity and Climate Change'. (Eds C. Dean, R. J. Harper and D. J. Eldridge.) pp. 156–165. (Rural Industries Research and Development Corporation: Barton, ACT.)

Charmley, E., Stephens, M. L., and Kennedy, P. M. (2008). Predicting livestock productivity and methane emissions in northern Australia: development of a bio-economic modelling approach. *Australian Journal of Experimental Agriculture* **48**, 109–113. doi:10.1071/EA07264

Chen, X., Hutley, L. B., and Eamus, D. (2005). Soil organic carbon content at a range of north Australian tropical savannas with contrasting site histories. *Plant and Soil* **268**, 161–171. doi:10.1007/s11104-004-0249-9

Cook, G. D. (1994). The fate of nutrients during fires in a tropical savanna. *Austral Ecology* **19**, 359–365. doi:10.1111/j.1442-9993.1994.tb00501.x

Cowley, R. A., Hearnden, M. H., Joyce, K. E., Tovar-Valencia, M., Cowley, T. M., Pettit, C. L., and Dyer, R. M. (2014). How hot? How often? Getting the fire frequency and timing right for optimal management of woody cover and pasture composition in northern Australian grazed tropical savannas. Kidman Springs Fire Experiment 1993–2013. *The Rangeland Journal* **36**, 323–345. doi:10.1071/RJ14030

Crowley, G., Garnett, S., and Shephard, S. (2009). Impact of storm-burning on *Melaleuca viridiflora* invasion of grasslands and grassy woodlands on Cape York Peninsula, Australia. *Austral Ecology* **34**, 196–209. doi:10.1111/j.1442-9993.2008.01921.x

CSIRO (2009). 'An Analysis of Greenhouse Gas Mitigation and Carbon Biosequestration Opportunities from Rural Land Use.' (CSIRO: St Lucia, Qld.)

Dalal, R. C., Harms, B. P., Krull, E., and Wang, W. J. (2005). Total soil organic matter and its labile pools following mulga (*Acacia aneura*) clearing for pasture development and cropping 1. Total and labile carbon. *Australian Journal of Soil Research* **43**, 13–20. doi:10.1071/SR04044

DCCEE (2010). 'Design of the Carbon Farming Initiative – Consultation Paper.' (Department of Climate Change and Energy Efficiency: Barton, ACT.)

DERM (2010). 'Land cover change in Queensland 2008–09: a Statewide Landcover and Trees Study (SLATS) Report, 2011.' (Department of Environment and Resource Management: Brisbane.)

DoE (2015). 'National Inventory Report 2013. Volume 1.' (Department of the Environment, Australian Government: Canberra, ACT.)

Donaghy, P., Bray, S., Gowen, R., Rolfe, J., Stephens, M., Hoffmann, M., and Stunzer, A. (2010). The bioeconomic potential for agroforestry in Australia's northern grazing systems. *Small-scale Forestry* **9**, 463–484. doi:10.1007/s11842-010-9126-y

DPI&F (2004). 'Stocktake: Balancing Supply and Demand.' (Department of Primary Industries and Fisheries: Queensland.)

DSITI (2016). SILO climate data. Department of Science, Information Technology and Innovation. Queensland Government. Available at: www.longpaddock.qld.gov.au/silo/ (accessed 11 January 2016).

Feller, C., and Beare, M. H. (1997). Physical control of soil organic matter dynamics in the tropics. *Geoderma* **79**, 69–116. doi:10.1016/S0016-7061(97)00039-6

Fraser, G. (2013). Improving the capacity to represent surface runoff processes in rangeland biophysical models. PhD Thesis. The University of Queensland, St Lucia, Qld, Australia.

Fraser, G. W., and Stone, G. S. (2016). The effect of soil and pasture attributes on rangeland infiltration rates in northern Australia. *The Rangeland Journal* **38**, in press.

Fraser, G. W., and Waters, D. K. (2004). Modelling runoff and erosion processes in central Queensland grazing lands. *In*: 'ISCO Conserving Soil and Water for Society: Sharing Solutions. 13th International Soil Conservation Organisation Conference'. Paper no. 749. (Eds S. R. Raine, A. J. W. Biggs, N. W. Menzies, D. M. Freebairn and P. E. Tolmie.) (ASSSI/IECA: Brisbane.)

Fujisaki, K., Perrin, A.-S., Desjardins, T., Bernoux, M., Balbino, L. C., and Brossard, M. (2015). From forest to cropland and pasture systems: a critical review of soil organic carbon stocks changes in Amazonia. *Global Change Biology* **21**, 2773–2786. doi:10.1111/gcb.12906

Fynn, R. W. S., Haynes, R. J., and O'Connor, T. G. (2003). Burning causes long-term changes in soil organic matter content of a South African grassland. *Soil Biology & Biochemistry* **35**, 677–687. doi:10.1016/S0038-0717(03)00054-3

Gleeson, T., Martin, P., and Mifsud, C. (2012). 'Northern Australian beef industry – assessment of risks and opportunities.' ABARES report to client prepared for the Northern Australia Ministerial Forum. (ABARES: Canberra.)

Gowen, R., and Bray, S. G. (2016). Bioeconomic modelling of woody regrowth carbon offset options in productive grazing systems. *The Rangeland Journal* **38**, in press.

Guo, L. B., and Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* **8**, 345–360. doi:10.1046/j.1354-1013.2002.00486.x

Hall, T. J., McIvor, J., Jones, P., MacLeod, N., McDonald, C., Reid, D., Smith, D., and Delaney, K. (2011). 'Investigating Intensive Grazing Systems in Northern Australia.' (Meat and Livestock Australia: North Sydney, NSW.)

Harms, B., and Dalal, R. (2003). 'Paired site sampling for soil carbon (and nitrogen) estimation – Queensland.' National Carbon Accounting System technical report no. 37. (Australian Greenhouse Office, Australian Government: Canberra, ACT.)

Harms, B. P., Dalal, R. C., and Cramp, A. P. (2005). Changes in soil carbon and soil nitrogen after tree clearing in the semi-arid rangelands of Queensland. *Australian Journal of Botany* **53**, 639–650. doi:10.1071/BT04154

Hassink, J. (1994). Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. *Soil Biology & Biochemistry* **26**, 1221–1231. doi:10.1016/0038-0717(94)90147-3

Holt, J. A. (1997). Grazing pressure and soil carbon, microbial biomass and enzyme activities in semi-arid northeastern Australia. *Applied Soil Ecology* **5**, 143–149. doi:10.1016/S0929-1393(96)00145-X

Hunt, L. P., McIvor, J. G., Grice, A. C., and Bray, S. G. (2014). Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points – a review. *The Rangeland Journal* **36**, 105–119. doi:10.1071/RJ13070

Isbell, R. F. (2002). 'The Australian Soil Classification.' Revised edn. (CSIRO Publishing: Melbourne.)

Janzen, H. H. (2004). Carbon cycling in earth systems-a soil science perspective. *Agriculture, Ecosystems & Environment* **104**, 399–417. doi:10.1016/j.agee.2004.01.040

Jeffrey, S. J., Carter, J. O., Moodie, K. B., and Beswick, A. R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**, 309–330. doi:10.1016/S1364-8152(01)00008-1

Karfs, R. A., Abbott, B. N., Scarth, P. F., and Wallace, J. F. (2009*a*). Land condition monitoring information for reef catchments: a new era. *The Rangeland Journal* **31**, 69–86. doi:10.1071/RJ08060

Karfs, R., Holloway, C., Pritchard, K., and Resing, J. (2009*b*). 'Land Condition Photo Standards for the Burdekin Dry Tropics Rangelands – a Guide for Practitioners.' (Burdekin Solutions Ltd and Queensland Department of Primary Industries and Fisheries: Townsville.)

Krull, E. G., and Bray, S. (2005). Assessment of vegetation change and landscape variability by using stable carbon isotopes of soil organic matter. *Australian Journal of Botany* **53**, 651–661. doi:10.1071/BT04124

Krull, E. S., Skjemstad, J. O., Burrows, W. H., Bray, S. G., Wynn, J. G., Bol, R., Spouncer, L., and Harms, B. (2005). Recent vegetation changes in central Queensland, Australia: evidence from delta13C and 14C analyses of soil organic matter. *Geoderma* **126**, 241–259. doi:10.1016/j.geoderma.2004.09.012

Krull, E., Bray, S., Harms, B., Baxter, N., Bol, R., and Farquhar, G. (2007). Development of a stable isotope index to assess decadal-scale vegetation change and application to woodlands of the Burdekin catchment, Australia. *Global Change Biology* **13**, 1455–1468. doi:10.1111/j.1365-2486.2007.01376.x

MacLeod, N. D., Ash, A. J., and McIvor, J. G. (2004). An economic assessment of the impact of grazing land condition on livestock performance in tropical woodlands. *The Rangeland Journal* **26**, 49–71. doi:10.1071/RJ04004

Marin-Spiotta, E., Silver, W. L., Swanston, C. W., and Ostertag, R. (2009). Soil organic matter dynamics during 80 years of reforestation of tropical pastures. *Global Change Biology* **15**, 1584–1597. doi:10.1111/j.1365-2486.2008.01805.x

McIvor, J. G., and Gardener, C. J. (1995). Pasture management in semi-arid tropical woodlands: effects on herbage yields and botanical composition. *Australian Journal of Experimental Agriculture* **35**, 705–715. doi:10.1071/EA9950705

McIvor, J. G., Ash, A. J., and Cook, G. D. (1995*a*). Land condition in the tropical tallgrass pasture lands. 1. Effects on herbage production. *The Rangeland Journal* **17**, 69–85. doi:10.1071/RJ9950069

McIvor, J. G., Williams, J., and Gardener, C. J. (1995*b*). Pasture management influences runoff and soil movement in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 55–65. doi:10.1071/EA9950055

McSherry, M. E., and Ritchie, M. E. (2013). Effects of grazing on grassland soil carbon: a global review. *Global Change Biology* **19**, 1347–1357. doi:10.1111/gcb.12144

MLA (2005). 'EDGENetwork Grazing Land Management – Burdekin Version Workshop Notes.' (Meat and Livestock Australia: North Sydney, NSW.)

NCST (2009). 'Australian Soil and Land Survey Field Handbook.' 3rd edn. (National Committee on Soil and Terrain, CSIRO Publishing: Melbourne.)

Northup, B. K., Brown, J. R., and Holt, J. A. (1999). Grazing impacts on the spatial distribution of soil microbial biomass around tussock grasses in a tropical grassland. *Applied Soil Ecology* **13**, 259–270. doi:10.1016/S0929-1393(99)00039-6

Northup, B., Brown, J., and Ash, A. (2005). Grazing impacts on spatial distribution of soil and herbaceous characteristics in an Australian tropical woodland. *Agroforestry Systems* **65**, 137–150. doi:10.1007/s10457-004-0002-7

O'Reagain, P., and Bushell, J. (2013). Managing for a variable environment: long term results from the Wambiana grazing trial. *In*: 'Proceedings of the Northern Beef Research Update Conference'. pp. 55–60. (North Australia Beef Research Council: Cairns, Qld.)

O'Reagain, P. O., Bushell, J., Holloway, C., and Reid, A. (2009). Managing for rainfall variability: effect of grazing strategy on cattle production in a dry tropical savanna. *Animal Production Science* **49**, 85–99. doi:10.1071/EA07187

O'Reagain, P., Bushell, J., and Holmes, B. (2011). Managing for rainfall variability: long-term profitability of different grazing strategies in a northern Australian tropical savanna. *Animal Production Science* **51**, 210–224. doi:10.1071/AN10106

O'Reagain, P., Scanlan, J., Hunt, L., Cowley, R., and Walsh, D. (2014). Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations. *The Rangeland Journal* **36**, 223–232. doi:10.1071/RJ13110

Orgill, S. E., Condon, J. R., Conyers, M. K., Greene, R. S. B., Morris, S. G., and Murphy, B. W. (2014). Sensitivity of soil carbon to management and environmental factors within Australian perennial pasture systems. *Geoderma* **214–215**, 70–79. doi:10.1016/j.geoderma.2013.10.001

Orr, D. M., and Phelps, D. G. (2013). Impacts of level of utilisation by grazing on an *Astrebla* (Mitchell grass) grassland in north-western Queensland between 1984 and 2010. 2. Plant species richness and abundance. *The Rangeland Journal* **35**, 17–28. doi:10.1071/RJ11069

Orr, D. M., McKeon, G. M., and Day, K. A. (1991). Burning and exclosure can rehabilitate degraded black speargrass (*Heteropogon contortus*) pastures. *Tropical Grasslands* **25**, 333–336.

Orr, D. M., Paton, C. J., and Lisle, A. T. (1997). Using fire to manage species composition in *Heteropogon contortus* (black speargrass) pastures 1. Burning regimes. *Australian Journal of Agricultural Research* **48**, 795–802. doi:10.1071/A96130

Orr, D. M., Burrows, W. H., Hendricksen, R. E., Clem, R. L., Back, P., Rutherford, M. T., Myles, D. J., and Conway, M. J. (2010*a*). Impacts of grazing management options on pasture and animal productivity in a *Heteropogon contortus* (black speargrass) pasture in central Queensland. 1. Pasture yield and composition. *Crop & Pasture Science* **61**, 170–181. doi:10.1071/CP09193

Orr, D. M., Yee, M. C., Rutherford, M. T., and Paton, C. J. (2010*b*). Impacts of grazing management options on pasture and animal productivity in a *Heteropogon contortus* (black speargrass) pasture in central Queensland. 2. Population dynamics of *Heteropogon contortus* and *Stylosanthes scabra* cv. Seca. *Crop & Pasture Science* **61**, 255–267. doi:10.1071/CP09194

Parton, W. J., Scurlock, J. M. O., Ojima, D.S., Schimel, D. S., and Hall, D. O. Scopegram Group Members (1995). Impact of climate change on grassland production and soil carbon worldwide. *Global Change Biology* **1**, 13–22. doi:10.1111/j.1365-2486.1995.tb00002.x

Pringle, M. J., Allen, D. E., Dalal, R. C., Payne, J. E., Mayer, D. G., O'Reagain, P., and Marchant, B. P. (2011). Soil carbon stock in the tropical rangelands of Australia: effects of soil type and grazing pressure, and determination of sampling requirement. *Geoderma* **167–168**, 261–273. doi:10.1016/j.geoderma.2011.09.001

Pringle, M. J., Allen, D. E., Phelps, D. G., Bray, S. G., Orton, T. G., and Dalal, R. C. (2014). The effect of pasture utilization rate on stocks of soil organic carbon and total nitrogen in a semi-arid tropical grassland. *Agriculture, Ecosystems & Environment* **195**, 83–90. doi:10.1016/j.agee.2014.05.013

Quirk, M. F., and McIvor, J. G. (2007). 'Grazing Land Management.' Technical manual. 2nd edn. (Meat and Livestock Australia: North Sydney, NSW.)

Rayment, G. E., and Lyons, D. J. (2011). 'Soil Chemical Methods: Australasia.' (CSIRO Publishing: Melbourne.)

Sanderman, J., Reseigh, J., Wurst, M., Young, M.-A., and Austin, J. (2015). Impacts of rotational grazing on soil carbon in native grass-based pastures in Southern Australia. *PLoS One* **10**, e0136157. doi:10.1371/journal.pone.0136157

Scanlan, J. C. (2002). Some aspects of tree-grass dynamics in Queenland's grazing lands. *The Rangeland Journal* **24**, 56–82. doi:10.1071/RJ02003

Scanlan, J. C., Pressland, A. J., and Myles, D. J. (1996). Run-off and soil movement on mid-slopes in north-east Queensland grazed woodlands. *The Rangeland Journal* **18**, 33–46. doi:10.1071/RJ9960033

Scanlan, J. C., MacLeod, N. D., and O'Reagain, P. J. (2013). Scaling results up from a plot and paddock scale to a property – a case study from a long-term grazing experiment in northern Australia. *The Rangeland Journal* **35**, 193–200. doi:10.1071/RJ12084

Schuman, G. E., Janzen, H. H., and Herrick, J. E. (2002). Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* **116**, 391–396. doi:10.1016/S0269-7491(01)00215-9

Segoli, M., Bray, S., Allen, D., Dalal, R., Watson, I., Ash, A., and O'Reagain, P. (2014). Managing cattle for sustainable soil properties: interactions between stocking rates and rainfall. *In*: 'Soil Change Matters'. (Ed. D. Victoria.) pp. 139–143. (Department of Environment and Primary Industries: Bendigo, Vic.)

Segoli, M., Bray, S., Allen, D., Dalal, R., Watson, I., Ash, A., and O'Reagain, P. (2015). Managing cattle grazing intensity: effects on soil organic matter and soil nitrogen. *Soil Research* **53**, 677–682. doi:10.1071/SR14236

Shaw, K. A., Rolfe, J. W., English, B. H., and Kernot, J. C. (2007). A contemporary assessment of land condition in the Northern Gulf region of Queensland. *Tropical Grasslands* **41**, 245–252.

Silburn, D. M., Carroll, C., Ciesiolka, C. A. A., deVoil, R. C., and Burger, P. (2011). Hillslope runoff and erosion on duplex soils in grazing lands in semi-arid central Queensland. I. Influences of cover, slope, and soil. *Soil Research* **49**, 105–117. doi:10.1071/SR09068

Sollins, P., Homann, P., and Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter: mechanisms and controls. *Geoderma* **74**, 65–105. doi:10.1016/S0016-7061(96)00036-5

Tothill, J. C., and Gillies, C. (1992). 'The pasture lands of northern Australia – their condition, productivity and sustainability.' Tropical Grassland Society of Australia, Occasional Publication No. 5. (Tropical Grassland Society of Australia: St Lucia.)

Tothill, J. C., Hargreaves, J. N. G., Jones, R. M., and McDonald, C. K. (1992). 'BOTANAL – a comprehensive sampling and computing procedure for estimating pasture yield and composition. 1. Field sampling.' Tropical Agronomy Technical Memorandum No. 78. (CSIRO: St Lucia.)

Viscarra Rossel, R. A., Webster, R., Bui, E. N., and Baldock, J. A. (2014). Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. *Global Change Biology* **20**, 2953–2970. doi:10.1111/gcb.12569

Walsh, D., and Cowley, R. (2016). Optimising beef business performance in northern Australia: what can 30 years of commercial innovation teach us? *The Rangeland Journal* **38**, in press.

Walsh, D., and Shotton, P. (2015). Cattle grazing found to have had no negative effect on soil carbon stocks at a site in the Northern Territory. *In*: '18th Biennial Conference of the Australian Rangeland Society'. Alice Springs, NT. (Ed. M. H. Friedel.) pp. 61. (Australian Rangeland Society: Alice Springs, NT.)

Waters, C. M., Melville, G. J., Orgill, S. E., and Alemseged, Y. (2015). The relationship between soil organic carbon and soil surface characteristics in the semi-arid rangelands of southern Australia. *The Rangeland Journal* **37**, 297–307. doi:10.1071/RJ14119

Whish, G., Pahl, L., and Bray, S. (2016). Productivity and economic implications of integrating carbon farming practices into a beef grazing property in central Queensland: regrowth. *The Rangeland Journal.*

Wilson, B. R., Growns, I., and Lemon, J. (2007). Scattered native trees and soil patterns in grazing land on the Northern Tablelands of New South Wales, Australia. *Soil Research* **45**, 199–205. doi:10.1071/SR07019

Witt, G. B., Noël, M. V., Bird, M. I., Beeton, R. J. S., and Menzies, N. W. (2011). Carbon sequestration and biodiversity restoration potential of semi-arid mulga lands of Australia interpreted from long-term grazing exclosures. *Agriculture, Ecosystems & Environment* **141**, 108–118. doi:10.1016/j.agee.2011.02.020

Zhang, K., Dang, H., Zhang, Q., and Cheng, X. (2015). Soil carbon dynamics following land-use change varied with temperature and precipitation gradients: evidence from stable isotopes. *Global Change Biology* **21**, 2762–2772. doi:10.1111/gcb.12886