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Managing cattle grazing intensity: effects on soil organic matter and soil nitrogen

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Abstract. Extensive cattle grazing is the dominant land use in northern Australia. It has been suggested that grazing intensity and rainfall have profound effects on the dynamics of soil nutrients in northern Australia's semi-arid rangelands. Previous studies have found positive, neutral and negative effects of grazing pressure on soil nutrients. These inconsistencies could be due to short-term experiments that do not capture the slow dynamics of some soil nutrients and the effects of interannual variability in rainfall. In a long-term cattle grazing trial in northern Australia on Brown Sodosol–Yellow Kandosol complex, we analysed soil organic matter and mineral nitrogen in surface soils (0–10 cm depth) 11, 12 and 16 years after trial establishment on experimental plots representing moderate stocking (stocked at the long-term carrying capacity for the region) and heavy stocking (stocked at twice the long-term carrying capacity). Higher soil organic matter was found under heavy stocking, although grazing treatment had little effect on mineral and total soil nitrogen. Interannual variability had a large effect on soil mineral nitrogen, but not on soil organic matter, suggesting that soil nitrogen levels observed in this soil complex may be affected by other indirect pathways, such as climate. The effect of interannual variability in rainfall and the effects of other soil types need to be explored further.

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Introduction

Many of northern Australia's soils are low in nutrients. This is because Australian landscapes are weathered relics of earlier pedological processes (Mott *et al*. 1985). In addition, northern Australia has a short and unreliable growing season and a long dry season, making it difficult for cropping to be practiced (Carberry *et al*. 1993). As a result, commercial cattle grazing is by far the dominant land use, by area, over much of northern Australia, occupying 2.5 million km^2 of tropical semi-arid savannas and grasslands (Cook *et al*. 2010). Because of this large area, grazing management practices that cause changes in soil nutrient dynamics could potentially affect national- or even global-scale processes. For example, it has been suggested that by improving land management, and hence land condition, in the livestock-grazed landscapes of northern Australia, hundreds of millions of tonnes of carbon could be sequestered in the top 10 cm of the soil (Ash *et al*. 1995; Garnaut 2008; Eady *et al*. 2009; Gifford 2010). In addition to helping reduce atmospheric CO_2 concentrations, this has the potential to improve soil and pasture productivity, improve livestock productivity and increase graziers' income through a higher value of livestock sales and incentives for carbon storage. This is especially important because grazing enterprises in north Australia are only marginally profitable (McLean *et al*. 2014). Finally, improving pasture and land condition can increase rainfall infiltration and decrease erosion, which is a major threat to the water quality of the Great Barrier Reef Lagoon (O'Reagain *et al*. 2005).

The soils of northern Australia are highly heterogeneous because of factors such as underlying geology, position in the landscape, climate and land use (Mott *et al*. 1985). Variations in soil properties may have a strong effect on pasture growth. For example, Mott *et al*. (1985) suggested that nitrogen was limiting for pasture growth on sesquioxidic soils, whereas soil water availability was limiting on the more fertile texture contrast soils. In other soils, water availability limited pasture growth in the drier years, whereas in wetter years pasture growth was limited by soil nitrogen (Mott *et al*. 1985). Furthermore, the effects of grazing depend on the soil type (McSherry and Ritchie 2013) and nutrient uptake by plants (Ash and McIvor 1995). For example, in northern Australia, higher grazing intensity was found to decrease soil carbon and nitrogen on Grey Vertosol and

Red Kandosol but to increase soil carbon on a Brown Sodosol–Yellow Kandosol complex (Pringle *et al*. 2011, 2014). Such variation suggests that the effects of grazing management on soil nutrient dynamics should consider local conditions and be extrapolated with caution.

Nitrogen and carbon dynamics are inextricably connected and cannot be understood independently of each other (Wedin 1995). The net amount of nitrogen mineralisation and availability to plants may be restricted by the high C : N ratio of soil organic matter (Mott *et al*. 1985; Wedin 1995). In addition, it has been suggested that there is a negative relationship between average rainfall and available nitrogen (Liebig *et al*. 2014). Therefore, it is important to manage the ecosystem for adequate available nitrogen. Even when soil nitrogen cannot be managed directly, it is important to understand its dynamics and drivers in order to better predict the amount of soil nitrogen, and consequently the amount of plant production and forage quality, under different management strategies. This information could be used by land owners to optimise their stocking rate and stocking strategies, leading to better management of their forage resource for animal productivity and maintaining land in good condition.

In northern Australia, grazing of native or introduced grasses and legumes without fertiliser application is the main management practice that affects nutrient dynamics and soil quality. It has been suggested that grazing affects soil nutrients through three main pathways in the absence of land degradation: (1) a net primary production pathway; (2) nitrogen pathways; and (3) decomposition pathways (Piñeiro *et al*. 2010). Because these pathways are not mutually exclusive and are affected by additional ecosystem properties, the effect of grazing on soil supply of nutrients is variable.

Manipulated field trials addressing the effects of grazing on soil supply of plant nutrients in the dry tropics are limited and often short term (Dalal and Carter 2000; Nelson and Roth 2004; for long-term studies, see Holt 1997; Pringle *et al*. 2011, 2014; Allen *et al*. 2013). However, it can take many years for some soil nutrients to respond to changes in land use or grazing intensity (Daryanto and Eldridge 2010; Segoli *et al*. 2012). Therefore, we took the opportunity of using soil samples collected in three different years from the dominant soil complex in an existing long-term grazing trial established in 1997 (O'Reagain *et al.* 2009) in order to study the effect of grazing intensity (i.e. stocking rates) and interannual rainfall variability on total soil nitrogen, mineral nitrogen and carbon.

In a previous study at the same location using data from a single sampling date, Pringle *et al.* (2011) showed that soil texture and stocking rate interact to affect soil organic carbon (SOC) stock. They found that the heavier grazing intensity treatment had a higher SOC stock in the dominant Brown Sodosol–Yellow Kandosol complex compared with the moderate grazing intensity treatment. Based on these results, we predicted that the heavy grazing treatment would have higher soil organic matter and lower soil nitrogen compared with the moderate grazing intensity treatment. However, interannual variation in rainfall may have a stronger effect on the soil's supply of plant nutrients, hence masking the long-term effects of grazing management in short-term studies.

Materials and methods

We used soil samples that were collected at a long-term cattle grazing trial conducted at Wambiana Station (20°34′S, 146°07′E), in north Queensland, Australia. The mean annual rainfall of the area is 636 mm, but is highly variable (Table 1), with most of the rainfall (70%) falling between December and March (O'Reagain *et al*. 2009). The area has been subjected to cattle grazing at light to moderate stocking rates for at least the past 130 years before the trial's establishment. In 1997, several ~100-ha paddocks were established to test a range of different grazing strategies (for more detail, see O'Reagain *et al*. 2009). Two contrasting strategies were selected for the present study: (1) a moderate stocking rate (MSR) treatment at ~8 ha per animal equivalent (450 kg steer), which is approximately the calculated long-term carrying capacity for the area; and (2) a heavy stocking rate (HSR) treatment at ~4 ha per animal equivalent (O'Reagain *et al.* 2009).

There are three major land types within the treatment paddocks, so to minimise this source of variability all soil samples were collected from the dominant *Eucalyptus brownii* savanna woodland on the Brown Sodosol–Yellow Kandosol complex (Northcote 1960; Cannon 1997; Isbell 2002), which covers approximately 55% of the site area. Two soil samples were collected to a 30 cm depth 2 years after the commencement of the trial and general soil properties measured (Table 2). Statistical inference cannot be performed from these limited soil samples, but they suggest that the two treatments were similar at the onset of the manipulation. The area sampled in the MSR and HSR treatments was a subsample of the area sampled by Pringle *et al.* (2011) and Bray *et al.* (2014). The area sampled is a relatively homogeneous area that had no apparent differences at the onset of the manipulations, with an arbitrary fence line dividing the grazing treatments. The vegetation consists of an open woodland of *E. brownii* and an understorey of the native shrub *Carissa ovata*. The grass layer is dominated by native C_4 tropical grasses, like *Bothriochloa ewartiana* and *Dichanthium fecundum*, but the exotic stoloniferous introduced grass *Bothriochloa pertusa* has spread widely on the trial area in the past 7–8 years. As a result of the grazing intensity treatment, there were major differences in both pasture total standing dry matter (TSDM) and pasture composition between the two treatments. On average, pasture TSDM was two- to threefold greater in the MSR (range 1324–3144 kg ha^{-1}) than in the HSR treatment (range 419–1090 kg ha^{-1}). At the same time, the relative contribution to yield of the more desirable perennial grasses like *B. ewartiana*

Table 1. Annual rainfall from July to June measured at the study area
For monthly rainfall see O'Reagain *et al.* (2009)

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Annual rainfall (mm year^{-1})	380	407	388	470	469	708	898	1032	715	1240	750	606

Table 2. Average of two soil samples that depict general soil properties (0–30 cm) in the moderate stocking rate (MSR) and heavy stocking rate (HSR) treatments on Brown Sodosol–Yellow Kandosol complex collected in 1999
EC, Electrical conductivity

Grazing strategy	pH	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Organic C (%)	EC (mS cm^{-1})	Phosphate (mg kg^{-1})	Potassium (%)
MSR	5.95	30	40	11	21	0.85	0.03	3.5	0.38
HSR	6.10	30	36	13	24	0.88	0.05	4.0	0.37

were approximately twofold greater in the MSR than HSR treatment. In contrast, the frequency and relative contribution to yield of the exotic *B. pertusa* was far higher in the HSR treatment (P. O'Reagain, unpubl. data; O'Reagain and Bushell 2011).

The soil samples were collected in July 2008, March–April 2009 and July 2013. Two adjacent 1-ha square-shaped areas (100 × 100 m) were selected on both sides of the arbitrary fence. In each area, 25 cores of 0–10 cm depth were sampled. However, because of a variety of issues, including missing or insufficient soil for laboratory analyses, the actual sample size was slightly lower (Table 3). Soil samples were dried at 40°C, large roots removed, soil crushed and passed through a 2-mm sieve. The dry soil was archived in sealed containers for further analysis.

Mineral N (ammonium and nitrate-N) was extracted from the soil by shaking 8 g soil in 20 mL potassium chloride (2 M) for 1 h and filtering through No. 41 filter paper. Nitrate and ammonium were determined in the KCl extracts by colourimetric methods (Best 1976; Keeney and Nelson 1982; Willis *et al*. 1993). Soil organic matter content was determined by the loss-on-ignition method (Segoli *et al*. 2012). Spain *et al*. (1982) demonstrated that loss-on-ignition provides a robust indicator of soil organic matter and organic carbon content in soils with low contents of carbonate and hydrous oxides, on similar soils to those examined herein.

The 2008 soils were subsampled to obtain total nitrogen and δ13C. Analysis was undertaken using an Isoprime isotope ratio mass spectrometer (IRMS) coupled to a Eurovector elemental analyser (Isoprime-EuroEA 3000, Isoprime Ltd, Stockport, UK) with HCl pre-treatment (concentration 10%) to remove carbonates (see Pringle *et al*. (2011), for further detail). Approximately 20 mg fine-ground soil was weighed into an 8 × 5 mm tin (Sn) capsule and analysed against a known set of standards (ANU Sucrose for ^{13}C).

The effects of grazing intensity were subjected to a *t*-test, and, when variances were significantly different between groups, a *t*-test with separate variance was performed (Zar 1999). The relationship between soil organic matter and $\delta^{13}C$ was analysed using Pearson correlation (Zar 1999). All statistical analyses were conducted using STATISTICA 12.0 software (StatSoft Inc., Tulsa, OK, USA).

Results

The soil organic matter content was higher in the heavy grazing treatment in all years (Fig. 1*a*), although this was only significant in 2008 and 2009 (2008: *t*-test t_{45} = –2.79, $P < 0.01$; 2009: *t*-test t_{46} = –2.74, $P < 0.01$; 2013: *t*-test t_{43} = –1.62, $P = 0.11$). Grazing treatment had no significant effect on the $\delta^{13}C$ signature in 2008 (Fig. 2; *t*-test $t_{45} = 0.44$, $P = 0.66$). However, $\delta^{13}C$ was negatively correlated with organic matter in 2008 (r = –0.50, $P < 0.01$).

Table 3. Number of soil samples analysed at 0–10 cm depth for the different soil measurements in the different years and in different treatments on Brown Sodosol–Yellow Kandosol complex
SOM, Soil organic matter; MSR, moderate stocking rate; HSR heavy stocking rate

Year	Grazing pressure	SOM	NO_3	NH_4
2008	MSR	22	25	25
2008	HSR	25	25	25
2009	MSR	25	25	25
2009	HSR	23	25	25
2013	MSR	25	25	25
2013	HSR	20	20	20

Nitrate content varied among the years (Fig. 1*b*) and was significantly higher in the moderate grazing treatment in 2008 and 2009 (2008: *t*-test t_{48} = –2.04, $P < 0.05$; 2009: *t*-test t_{48} = –2.35, $P = 0.02$; 2013: *t*-test t_{43} = –0.90, $P = 0.37$).

Ammonium content also varied among years (Fig. 1*c*). Ammonium content was higher in the heavy grazing treatment in 2008 and 2009, but was lower in the heavy grazing treatment in 2013 (2008: *t*-test with separate variance $t_{31,25}$ = –2.73, $P = 0.01$; 2009: *t*-test with separate variance $t_{35,59}$ = –3.28, $P < 0.01$; 2013: *t*-test with separate variance $t_{30,41} = 2.59$, $P = 0.01$).

Grazing treatment had no significant effect on the total nitrogen content in 2008 (Fig. 3; *t*-test $t_{45} = 1.15$, $P = 0.26$).

Discussion

Commercial grazing is the dominant land use in the tropical semi-arid ecosystems of northern Australia (Cook *et al*. 2010). It is expected that grazing management will affect nutrient cycling in soils. We used a long-term grazing trial to test the effects of cattle stocking rates on interannual differences in soil organic matter, soil total nitrogen and soil mineral nitrogen. The results suggest that on Brown Sodosol–Yellow Kandosol complex, the HSR treatment had higher soil organic matter compared with the MSR treatment, consistent with Pringle *et al*. (2011), and with little interannual variability (Fig. 1*a*). The relatively small increase in soil organic matter under the HSR suggests a negligible ecological effect at the local scale. However, extrapolation of this small change over the large area occupied by commercial cattle grazing in northern Australia could affect national- or even global-scale processes (Ash *et al*. 1995). In contrast with soil organic matter, interannual variability was greater for soil mineral nitrogen, with no consistent effect of grazing treatment (Fig. 1*b*, *c*). This suggests that soil mineral nitrogen is relatively resistant to grazing, even at different rainfall intensities.

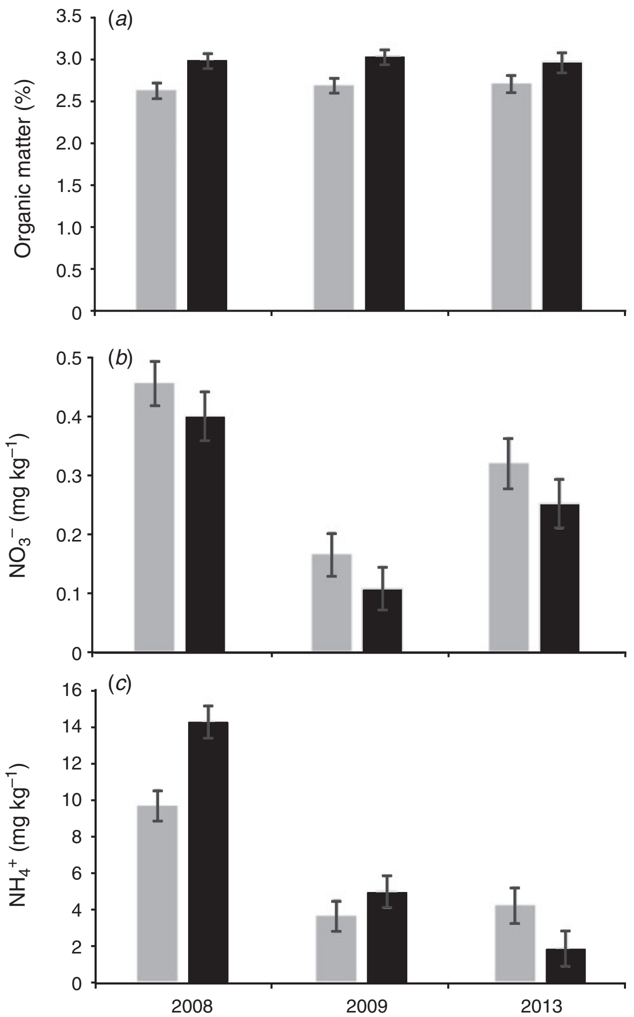

Fig. 1. (*a*) Soil organic matter, (*b*) nitrate, and (*c*) ammonium contents at 0–10 cm soil depth under moderate (grey) and heavy (black) grazing intensity rates on Brown Sodosol–Yellow Kandosol complex in 2008, 2009 and 2013. Data are the mean ± s.e.

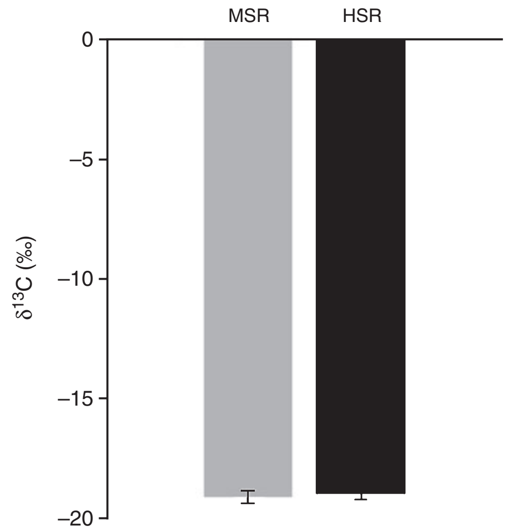

Fig. 2. δ^{13}C values at 0–10 cm soil depth under moderate and heavy stocking rates (MSR and HSR, respectively) on Brown Sodosol–Yellow Kandosol complex in 2008. Data are the mean ± s.e.

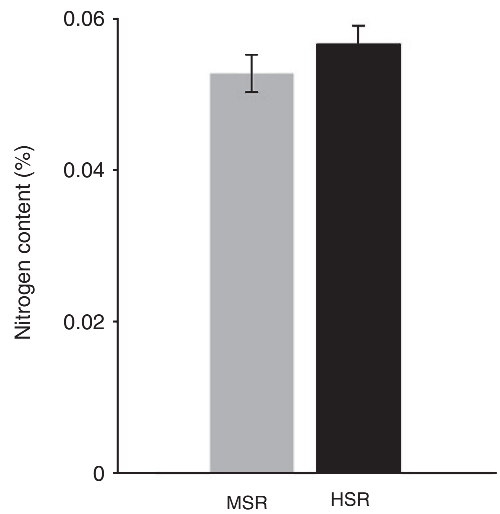

Fig. 3. Total soil nitrogen content at 0–10 cm soil depth under moderate and heavy stocking rates (MSR and HSR, respectively) on Brown Sodosol–Yellow Kandosol complex in 2008. Data are the mean ± s.e.

Pringle *et al.* (2011) explained the higher SOC in the HSR on this soil complex by a lower δ^{13}C signature, suggesting a higher contribution to SOC from C_3 shrubs and trees relative to the C_4 perennial grasses (Krull and Bray 2005). After a fire in the treatments in 1999, the cover of the sprawling shrub *C. ovata* increased faster in the HSR than MSR treatment (Bray *et al.* 2014), but there was no significant difference in the total woody vegetation cover between the treatments (Bray *et al.* 2014; P. O'Reagain, unpubl. data). Preliminary soil analyses suggest that soil under *C. ovata* shrubs contains more carbon than surrounding soil (S. Bray, unpubl. data). The present data support the conclusions of Pringle *et al.* (2011) because we found a negative correlation between δ^{13}C and soil organic matter, although no significant difference in δ^{13}C was found between the grazing treatments. It is possible that our finding reflects the effects of depth and spatial scale on the strength of the correlation, or that the present experiment was too short to detect the effects of grazing on δ^{13}C in total organic carbon (Pringle *et al.* 2011). Perhaps examining the δ^{13}C by aggregate fractions could enhance the sensitivity and enable detection of the effects of grazing (Krull and Bray 2005).

The results found in the Brown Sodosol–Yellow Kandosol complex at the Wambiana site are not consistent with other soil organic matter studies on different soils in northern Australia (Ash *et al.* 1995; Holt 1997; Badgery *et al.* 2013; Cowie *et al.* 2013; Pringle *et al.* 2014). For example, Pringle *et al.* (2011) found that SOC stocks (soil organic C concentration × bulk density × soil depth) at 0–10 cm depth were lower under high than low stocking rates on different soil types, namely a Grey Vertosol and a Red Kandosol, at the same trial site. In a recent survey of 98 sites, Allen *et al.* (2013) found a small but significant negative relationship between stocking rates and SOC. However, they concluded that the main drivers for SOC were climate and soil type. It was suggested that stocking rates affect SOC through changes in TSDM, grass species composition and root mass (O'Reagain and Bushell 2011; Badgery *et al*. 2013). In another long-term 26-year study of sheep grazing intensity on a Grey Vertosol, Pringle *et al*. (2014) found no significant difference in SOC stocks between six pasture utilisation rates ranging from 0% (exclosure) to 80% utilisation. However, there was a significant loss of total nitrogen from the topsoil under intensive pasture utilisation. Furthermore, a slight visual trend of declining SOC was found at higher utilisation rates.

The variability and inconsistency of results within and between studies across northern Australia indicate that caution is required when making claims on the benefits of improved grazing management on soil C stocks and nutrients in northern Australia. Although heavy grazing increased SOC on one soil in the present study, most other studies have found that heavy grazing can have severe negative effects, such as increased soil erosion (Eldridge 1998; O'Reagain *et al*. 2005), woody encroachment (Daryanto *et al*. 2013), changed species composition (Orr *et al*. 2010; Ash *et al*. 2011; Orr and Phelps 2013), reduced ground cover and soil surface condition (Ash *et al*. 2011). In addition, it has been shown that, in the longer term, heavy grazing reduces animal production and profitability (O'Reagain *et al*. 2009; O'Reagain and Bushell 2011).

In addition, combining these results with other results from different soils can increase the predictive value of models, which are important for underpinning the calculation of Australia's national greenhouse accounts. National predictions of the effects of land use change need to include soil type in their assessments to reduce uncertainties and errors (Segoli *et al*. 2013). Furthermore, it is important for the landowner to know which soils are likely to sequester carbon with changes in land use. More research is needed on different soil types and variability within paddocks in order to build a practical managerial plan and make more accurate predictions on the long-term consequences of different management systems on soil carbon, carbon sequestration and greenhouse gas accounting. Special attention should be given to the effect of woody vegetation on soil carbon.

The interannual variability in soil nitrate content was greater than the effect of grazing intensity, probably because of the natural variability of nitrate content at seasonal and annual time scales (Liebig *et al*. 2014). For example, the lower nitrate content in 2009 than the other two years may reflect sampling season, because 2009 sampling was performed during the growing season when nitrate uptake by plants would be high as opposed to the other years, when the sampling was performed in the dry season (Chen *et al*. 2001). The higher amount of nitrate and ammonium in 2008 could be explained by the below-average rainfall observed during previous years (Table 1) that caused an accumulation of mineral nitrogen (Liebig *et al*. 2014). An absence of reliable measured data before the commencement of the experimental grazing trial restricts our capacity to attribute observed changes to long-term management. However, the fact that no biologically meaningful differences in mineral nitrogen were apparent after 20 years suggests that climate, rather than grazing intensity, is the main driver of mineral nitrogen dynamics. This is probable because atmospheric deposition is the dominant source of reactive nitrogen (Bobbink *et al*. 2010) and most of the plant nutrients consumed by livestock return to the soil (Chen *et al*. 2001). This also emphasises the importance of studying the effect of rainfall on soil nitrogen and the carry-over effect from previous years (Liebig *et al*. 2014). Better understanding of the dynamics of soil nitrogen and its drivers should improve our ability to predict levels of available soil nitrogen. This will likely lead to better management of stocking rates and grazing strategies that increase profitability and reduce land degradation.

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