Agroforestry System (2005) 65:137–150
DOI 10.1007/s10457-004-0002-7

Grazing impacts on spatial distribution of soil and herbaceous characteristics in an Australian tropical woodland

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Received 10 May 2004; accepted in revised form 30 December 2004

Key words: Eucalypt woodlands, Grazing pressure, Land condition, Plant–soil interactions, Silvopasture, Soil properties

Abstract

This study examined effects of different levels of applied grazing pressures on herbaceous vegetation (standing crop, basal area, size and spacing of grass tussocks) and soil properties (total soil C, total N, total P, and soil-borne plant material [roots and surface litter] in the A horizon) around grass tussocks of a dry eucalypt woodland (dominant woody components; *Eucalyptus xanthoclada* and *Corymbia erythrophloia* of northern Australia. Grass tussocks influenced total soil C and N at small (< 20 cm) spatial scales, and applied grazing pressures significantly ($p < 0.05$) affected all soil properties except total P. Concentrations of N and C were highest at locations close to plants, and levels in proximity to plants declined under sustained heavy grazing. Paddocks receiving heavier grazing pressures also produced less standing crop and tussocks were smaller and more widely dispersed. Further, areas with high amounts of soil C, N and soil-borne plant materials were smaller and more widely dispersed under heavy grazing. Alternatively, conservative grazing pressure in combination with wet season grazing deferments allowed conservation of landscape condition. Eucalypt woodlands in northern Australia have low resistance to disturbance, and limited resilience to recover following disturbance. As such, the effects of disturbance on these areas should be monitored by combinations of plant (basal area, plant spacing) and soil (soil-borne plant material, total N) characteristics capable of detecting degradation at the earliest stages possible.

Introduction

Open eucalypt woodlands are the dominant vegetation types in the sub-humid tropical zones of northern Australia, and have been used for grazing beef cattle since European settlement (approximately 1870). Pastoralists in northern Australia traditionally relied on low-input use of undeveloped paddocks of native grasses, with herd size balanced by limited forage quality and drought-induced mortality (Gardener et al. 1990). However, the search for economic viability has resulted in the incorporation of paddocks of grazing-tolerant introduced forages, improved animal genetics and supplemental feeds into these silvopastoral systems (Gardener et al. 1990). The upshot has been increased on-property retention times of animals, greater stock survival during drought, and increases in applied stocking rates (Brown and Ash 1996). In response, paddocks of native grasses that are components of these properties have suffered degradation (Tothill and Gillies 1992) through inappropriate management of grazing pressure, particularly in response to ecosystem and climatic variability (Williams et al. 1993; Brown and Ash 1996).

Soils in northern Australia are old, fragile and inherently low in carbon, nutrients and organic matter (Ahern et al. 1994) and depend on the limited plant growth that occurs to help maintain condition (Williams et al. 1993). Vegetation promotes ecosystem stability in northern Australia by enhancing the movement of important resources (water, nutrients) into the soil, limiting erosion, enhancing soil biological activity and the cycling of nutrients (Ludwig et al. 1994; Holt et al. 1996). Trees in eucalypt woodlands are widely dispersed across these landscapes, and can have large-scale (several meters) horizontal and vertical effects on soils (Jackson and Ash 1998). Alternatively, tussocks of native perennial grasses, and patches of grasses, may have similar but more localised effects on soil processes in herbaceous-dominated areas. Tongway and Ludwig (1994) reported localised enrichment of mineral N and P, and soil C in close proximity to tussocks in semi-arid Australian plant communities, compared to areas without plants. Higher levels of soil micro- and macrofaunal activity have also been reported for areas in proximity to plants, compared to neighbouring bare spaces (Holt et al. 1996; Northup et al. 1999), and declines noted in response to disturbance. These localised distributions of soil resources and biological activity shows the importance of understanding spatial organisation of soil resources within a landscape, and the effects of disturbance on such distributions. However, the impact of individual tussocks or bare spaces within patches on fine-scale spatial distribution of soil characteristics in northeast Queensland, particularly in response to grazing management and grazing history, has not been widely studied.

Proper use of grazing lands in the Australian tropics requires identification of management techniques that are sustainable on an ecosystem basis (Brown and Ash 1996), and the development of useful indicators of land condition (Williams et al. 1993; Whitford et al. 1998). To examine the usefulness of potential indicators, we undertook a study to describe inter-relationships that might exist between grass tussocks and soil chemical properties, and their responses to grazing during a period of dry growing conditions. Our objective was to quantify the effect of current grazing pressures, in combination with grazing histories (approximately 10 years) prior to the study, on grass tussocks and corresponding distributions of soil properties at scales (< 2 m^{-2} area) below the micro-patch (Noble and Brown 1997). A second objective was to determine if potentially useful soil-plant indicators of disturbance could be developed.

Materials and methods

Study site

Data were collected from experimental paddocks (1.2–2.3 ha in size) within the CSIRO Cardigan research sites (~75 ha) located (20°11′ S; 146°43′ E) in northern Queensland (McIvor and Gardener 1991), Australia. The sites (240 m elevation) occupy areas consisting of broad ridges bisected by creeks, with < 25 m change in elevation and 3–5% slopes. The paddocks were generally rectangular in shape, with long axes oriented across slopes. Soils (Table 1) are Haplic Eutrophic Red Chromosols (oxic Paleustalfs) that developed on granodiorite formations (Isbell 1996), and are considered of moderate fertility [11 ($\pm$7) mg kg^{-1} total mineral N, 7 ($\pm$3) mg kg^{-1} mineral P] for northern Queensland (Ahern et al. 1994). Red Chromosol soils are diverse and found throughout north Queensland. Land types with these soils occupy roughly 1.0×10^6 ha^{-1}. The climate is sub-humid tropical, with measured average ($\pm$s.d.) annual (1984–1997) precipitation of 527($\pm$164) mm, and evaporation of 1801($\pm$225) mm. Roughly 80% of precipitation is received as monsoon rains during December through April. Mean minimum/maximum temperatures in summer and winter were 21/34 °C and 11/24 °C, respectively.

The plant community (Table 2) is described as dry tropical eucalypt woodland. The woody component was comprised of five tree and seven shrub species (McIvor and Gardener 1991). It was dominated by ironbark (*Eucalyptus xanthoclada* Brooker & A.R. Beau.) and bloodwood [*Corymbia erythrophloia* (Blakely) K.D. Hill & L.A.S. Johnson] trees to 20 m height with diffuse, open canopies.

Table 1. Description of common soil profile at the CSIRO Cardigan research site, Queensland, Australia.[a]

Horizon	Depth (cm)	Particle fractions[b]				CEC[c] ms/cm	EC[d] ms/cm	pH[d] ms/cm	Colour	Texture[e]	Structure
		Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)						
A	0–11	45	28	8	16	9.1	0.05	6.7	Red-Brown (6.5YR3/3)	SCL	Weak 10–20 mm angular blocky
B_1	11–25	44	26	5	23	13.1	0.04	6.8	Red (2.5YR3/5)	SC	Weak 20–50 mm angular blocky
B_{21}	25–50	25	13	3	58	15.1	0.05	6.7	Red (2.5YR3/6)	MC	Strong 20–50 mm angular blocky; breaks to strong 2–5 mm angular blocky
B_{22}	50–75	23	8	4	64	NR	0.03	7.2	Red (2.5YR3/6)	MC	Strong 20–50 mm angular blocky; breaks to strong 2–5 mm angular blocky
B_{23}	75–100	30	13	6	49	NR	0.04	7.5	Red (2.5YR3/6)	MC	Moderate 50–100 mm lenticular breaking to moderate 20–50 mm angular blocky
BC	100–110	32	22	10	34	NR	0.04	7.7	Yellow-Red (5YR4/6)	SCL	Coarse sandy; moderate 50–100 mm lenticular breaking to moderate 20–50 mm angular blocky
C	110–120 +120	43	26	9	19	NR	0.03	7.9		SCL	Coarse sandy; massive Granodiorite

[a]Description was derived from profiles defined in McIvor and Gardener (1991).
[b]Particle size fractions determined by pipette method; the remainder for each horizon was gravel.
[c]Cation exchange capacity in NH_4Oac at pH 7.0; NR = not recorded.
[d]Electrical conductivity and pH in a 1:5 soil:water suspension.
[e]MC = medium clay; SC = silty clay; SCL = silty clay loam.

Table 2. Plant community characteristics of the CSIRO Cardigan research site, Queensland, Australia.

Characteristics[a]	x̄ (±1 s.d.)
Tree density, no ha^{-1}	127 (45)
Trunk basal area, m^{-2} ha^{-1}	3.5 (0.8)
Herbaceous species, no m^{-2}	9.3 (7.5)
Tree species, no	6
Shrub species, no	8
Grass species, no[b]	29
Forb species, no	56

[a]Developed from values reported in McIvor and Gardener (1991).
[b]Fifteen of the grass species were perennials.

The understorey was a mixture of 85 herbaceous species. Ground cover was organised in discontinuous cross-slope bands, with size and coverage dependent on land condition (Northup et al. 2005). Dominant herbaceous species included desert bluegrass [*Bothriochloa ewartiana* (Domin) C.E. Hubb], golden beardgrass (*Chrysopogon fallax* S.T. Blake), black speargrass [*Heteropogon contortus* (L.) P. Beauv. ex Roem & Schult], and kangaroo grass (*Themeda triandra* Forrskul). Wiregrasses (*Aristida* spp.), and the introduced (and invasive) stoloniferous grass Indian couch [*Bothriochloa pertusa* (L.) A. Camus] were also common on degraded areas. The median expected growing season is 14 weeks (McIvor and Gardener 1991).

Experimental design

Paddocks on land in two condition classes (States 1 and 2) were included in the study. Paddocks on State 1 (S1) land (40 ha^{-1}) were not grazed during 1983–1993, and native perennial grasses dominated ground cover. State 2 (S2) land (~35 ha^{-1}) had received heavy grazing pressure at commercially applied stocking rates during 1983–1993, and ground cover was dominated by early-succession native grasses (annual and perennial), *B. pertusa*, and annual forbs. The State 1 – State 2 division of condition was based on conceptual state and transition models used to describe vegetation responses in tropical tallgrass zones of northern Australia. These classes also represented current condition of large areas of north Queensland (Tothill and Gillies 1992).

Paddocks on two replicate blocks (top and bottom of slopes) within each land class were randomly assigned to different grazing treatments in 1993 and sustained through 1997 (Table 3). Treatments applied to S1 paddocks were non-grazed controls (UG, to serve as the standard for excellent land condition), lightly grazed (LG), and heavily grazed following early wet season deferments (SG). The S1 paddocks were in similar condition [1530 (±495) kg ha^{-1} herbaceous standing crop; 1.7 (±0.3)% herbaceous basal area] at the start of treatments. Grazing treatments applied to S2 paddocks were lightly grazed following wet season deferment (LG), and heavily grazed without deferment (HG, continuation of the previous 10 years regime). State 2 paddocks were in similar condition at the start of treatments [93 (±20) kg ha^{-1} herbaceous standing crop; 0.6 (±0.2)% herbaceous basal area]. Hereafter, treatments are referred to by paddock condition in 1997 (intact, stable and degrading

Table 3. Grazing treatments applied to experimental paddocks on the CSIRO Cardigan research site, Queensland, Australia, and 1997 descriptions of paddock condition.

Grazing treatments[a]	Paddock management			State[e]	Paddock condition
	Utilisation level[b] (%)	Stocking rate[c] (ha AU^{-1})	Grazing deferment[d]		
S1-UG		0.0		1	Intact
S1-LG	25	10.2	+	1	Stable
S1-SG	75	3.4	+	1	Degrading
S2-LG	25	10.2	+	2	Recovering
S2-HG	75	3.4	–	2	Degraded

[a]S1 = historically lightly grazed sites, and S2 = historically heavily grazed sites. UG = ungrazed control; LG = light seasonal grazing; SG = heavy seasonal grazing; HG = continual heavy grazing without deferment.
[b]Utilisation of current years herbage.
[c]One animal unit (AU) was equivalent to 454 kg of yearling cattle. Stocking rates are adjusted to an annual basis.
[d]Deferment of grazing during the first half of the wet season (December-April).
[e]State condition of conceptual state and transition models developed for northern Australia.

on S1 lands; degraded and recovering on S2 lands).

Data collection

Plant responses

Herbaceous standing crop and basal area (percent soil surface occupied by perennial tussocks) in paddocks were described by BOTANAL procedures on 200, 0.5 m^{-2} quadrats along two fixed 100 m transects, oriented across slopes, in June of 1993 and 1997. BOTANAL is a double sampling technique, based on dry-weight-rank procedures, used to measure and analyse plant community attributes (Friedel et al. 2000). In July 1997 measurements of individual plants were collected. *B. ewartiana* tussocks were located by randomly chosen x, y coordinates ($n = 50$ per paddock), and measured to determine amount of surface area containing living tillers. Also, distances between randomly located *B. ewartiana* tussocks ($n = 100$) and the nearest neighbour *B. ewartiana* in each of four quadrants were measured to calculate interplant distances.

Soil experiment one: units of measure

Twelve replicate locations were identified in an area (~15 ha) that had largely been excluded from grazing during 1984–1997. Each location was centred on scalds (5–34 m in diameter) that existed in areas otherwise considered to be in excellent condition. Scalds are degraded areas that form in response to disturbance including; dry season fires, drought, erosion following intense downpours, grazing, or a combination of disturbances (Bridge et al. 1983). Scalds have shallow A horizons, limited soil resources, microbial activity or plant growth, and tightly sealed bare surfaces. While there was no record for length of existence of the sampled scalds, technical staff involved in site management had not noted perennial grasses occupying the larger scalds ($n = 3$) since 1984. Alternatively, Bridge et al. (1983) experimentally produced scalds within 3 years on a site northwest (14°6′ C, 132°2′ E) of our location, so it can be surmised that the sampled scalds had likely existed for 3–13 years.

At each location, examples of two additional sub-patch units (in addition to scalds) were randomly located; areas within 15 cm of centres of native grass tussocks (*B. ewartania* or *C. fallax*), and centres of bare interspaces (~0.6 m diameter) between neighbouring tussocks. Duplicate soil cores (10 × 10 cm) were collected from the upper 12 cm of the soil profile of each replicate, and placed in Ziploc bags for storage and transport. Bulk density was determined after drying (105 °C) samples to a constant weight. Samples were sieved (1.4 mm) to remove coarse roots and litter, ground, and analysed for total soil nitrogen and carbon, as described in laboratory analyses. Pool-scale (mg m^{-2}) C and N were calculated by multiplying concentrations, bulk density and depth. Results were used to determine whether concentration (mg kg^{-2}) or pool (mg m^{-2}) scale information possessed the sensitivity required to define differences among these three divergent units.

Soil experiment two: micro-patch response

Soil samples (5.0 cm diameter by 7.5 cm depth) were collected at four locations, found by randomly chosen x, y coordinates during September 1997 in intact, degrading and degraded paddocks. At each location, the closest *B. ewartiana* tussock was identified, and samples were collected along transects (Figure la) between centres of the identified plants and their closest neighbour *B. ewartiana* tussock. Samples were collected in tussock centres (UC and DC for up- and down-slope, respectively) and the periphery of tussocks (UE and DE for up- and down-slope edges, respectively), centre of transects in interspaces (TC), and additional locations at 1/3 and 2/3 the distance between tussock edges and transect centres. Composite samples were developed for locations along transects and analysed for total soil C, N, and P. Additional samples were collected from a second randomly located set of micro-patches, and soil-borne plant materials (referred to as roots and surface litter) were washed from samples through 2 mm sieves and oven-dried (105 °C) to a constant weight.

Soil experiment three: individual unit response

Soil samples were collected at locations ($n = 8$), found by randomly chosen x, y coordinates, in each paddock during October through November 1997. At each location, the closest of one of two randomly chosen units were located; *B. ewartiana* tussocks ± 30 cm of neighbouring soil (Figure 1b), and interspaces (Figure 1c) between *B. ewartiana*

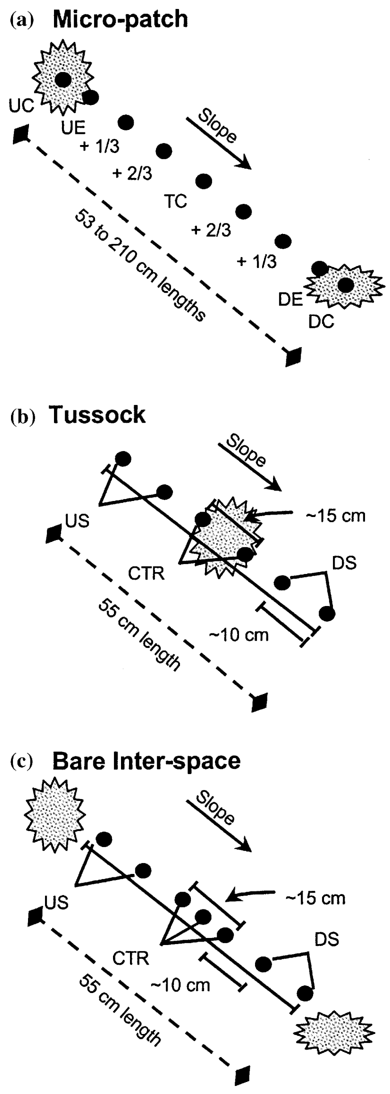

Figure 1. Orientation of transects used to sample (a) micro-patch, (b) tussock, and (c) bare inter-space units within micro-patches; UC and UE are upslope centre and edge of tussocks within micro-patches, DC and DE are down-slope centre and edge of tussocks, TC is transect centre, +1/3 and +2/3 are equi-distant locations between tussock edges and transect centres; US, DS and CTR are upslope, down-slope and centre locations of units within micro-patches.

tussocks (±30 cm at centres of bare spaces between neighbouring plants). Soil cores (7.5 cm depth by 5.0 cm diameter) were collected at different locations along transects, oriented parallel to the slope that bisected the sampled units. Cores were used to develop composite samples for centres of micro-patch units (CTR), and zones upslope (US) and down slope (DS) of centres, and analysed for total soil C, N and P as reported in the laboratory analysis section. Samples were collected from an additional set of randomly located tussocks and interspaces to define soil-borne plant material (plant roots and surface litter) as in experiment two.

The different micro-patch and within patch units, and arrangement of sample locations, in experiments two and three allowed comparisons of run on (localised sinks near grass tussocks) and runoff (bare spaces in proximity to plants that act as sources of water and nutrients) zones thought to be involved in the concentration of soil resources and soil biological activity near grass tussocks (Tongway and Ludwig 1997). Soil sampling was restricted to the upper 7.5 cm because it was the most resource-rich segment of the profile and represented most of the A horizon (McIvor and Gardener 1991). Further, other studies in northern Australia have recorded the highest levels of soil resources within this segment (Bridge et al. 1983; Tongway and Ludwig 1994). Also, management impacts would most likely be recordable in this zone following 5 years of applied treatments. *B. ewartiana* was the only species included in all experiments because it was a key component of the herbaceous community, actively responded to grazing regimes (Northup et al. 2003), and could be found within all study paddocks.

Laboratory analyses

Soil samples were passed through a 1.4 mm sieve to remove plant materials and gravel, and ground by mortar and pestle. Total N was determined by micro-Kjeldahl techniques, and total P was described by first igniting samples in a 550 °C oven for 2 h then extracting with 0.5 M H_2SO_4 for 16 h (Rayment and Higginson 1992). Soil C was determined by low temperature (375 °C for 20 h) ignition and adjusted to wet oxidation equivalents (Rayment and Higginson 1992) with a predictive equation [C (mg kg^{-1} drysoil) = 2381.2 + 0.49 (ignited C, mg kg^{-1} dry soil); $r^2 = 0.89$, $p < 0.01$), $n = 124$] developed with samples collected from an array of paddocks in different condition. Amounts for all wet chemistry determinations were described by colourimetric techniques.

Statistical analyses

Plant responses (standing crop, basal areas, interplant distances) were analysed by one-way analyses of variance (ANOVA) to test paddock-scale grazing effects on herbaceous vegetation (Statsoft Inc. 1998). Concentration and pool-scale measures of soil C and N (experiment one) were analysed in a completely randomised design with locations as replicates ($n = 12$) and patch type ($n = 3$) the main effects. Significance ($p < 0.05$) of responses was tested with Fisher's protected LSD, and sensitivity of contrasts to differences in amounts was considered.

Total soil C, N, P, and roots-litter from micro-patches (experiment two) were analysed as randomised complete blocks with split-plots by GLM procedures (Statsoft Inc. 1998). Blocks ($n = 2$) and grazing treatments ($n = 3$) were main effects and location along transects ($n = 9$) the split-plot. Soil chemical properties and roots-litter around individual units within micro-patches (experiment three) were analysed as split–split plots within randomised blocks. Blocks ($n = 2$) and grazing treatments ($n = 5$) were main effects, individual units the split-plot, and locations around units ($n = 3$) the split–split plot. The split-plot and split–split plot analyses used in experiments two and three, respectively, were considered replications in space and tested with the appropriate models. Significant ($p < 0.05$) effects were examined with Fisher's protected LSD.

Results

Rainfall and vegetation responses

Rainfall was equal to or below average during 1993–1997, with drought conditions recorded in 1993 and 1994 (Figure 2). Evaporation was equal to or above the long-term average, and 3.5-fold greater than rainfall. Intact paddocks had the highest ($p < 0.05$) standing crop during 1997 (2100 kg ha^{-1}), while the second highest levels were for a group containing intact (1993), stable (1993, 1997) and recovering (1997) paddocks (Table 4). Basal area was greater on intact and stable paddocks than the degrading, degraded or recovering paddocks. In 1997, individual *B. ewartiana* tussocks on intact paddocks were significantly ($p < 0.05$) larger than the remaining paddocks, and the smallest live tussock areas were recorded on degraded paddocks. Living basal area of tussocks on recovering paddocks was similar to degrading paddocks. Distances between neighbouring tussocks were largest on degraded paddocks, compared to the remaining paddocks.

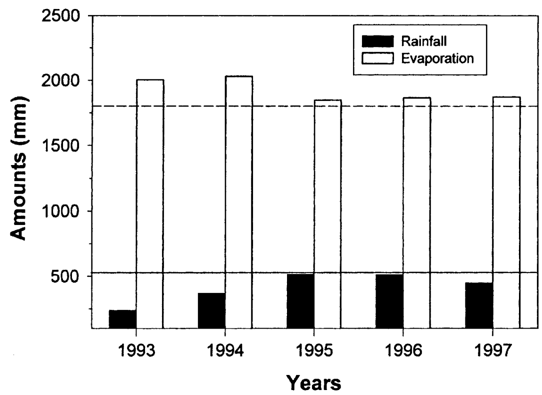

Figure 2. Measured rainfall and evaporation on the CSIRO Cardigan research site, northern Queensland, Australia during 1993 through 1997. Long-term (1984–1997) annual rainfall and evaporation, respectively, are represented by the solid and dashed lines.

Soil properties

Experiment one

Soil bulk density (± 1 s.d.) was highest on scalds [1.52 (± 0.07)g cm^{-3}] and lowest [1.36 (± 0.05)g cm^{-3}] in close proximity to tussocks (Figure 3a). Centres of bare interspaces between tussocks had bulk densities intermediate between scalds and tussocks [1.44 (± 0.06)g cm^{-3}]. Concentration of total soil carbon showed significant ($p < 0.05$) unit effects (Figure 3b), with concentrations in areas adjacent to tussocks, interspaces between tussocks and scalds all different. Alternatively, pool-scale C indicated tussocks and bare interspaces were similar and different from scalds, which could not be differentiated from interspaces. Significant unit effects were also noted in concentration of total soil N, with N in areas adjacent to tussocks, interspaces between tussocks and scalds all different (Figure 3c). There was no statistical difference ($p > 0.05$) between units in pool-scale N. Due to

Table 4. Responses of herbaceous characteristics in experimental paddocks on the CSIRO Cardigan research site, Queensland, Australia, to grazing treatments.[a]

Paddock condition	Paddock characteristics[b]				*B. ewartiana* Tussocks[c]	
	Standing crop		Herbaceous basal area (%)		Inter-plant distance (cm)	Plant basal area (cm^{-2})
	1993	1997	1993	1997		
Intact	1737 ab	2100 a	1.7 a	1.7 a	53 b	80 a
Stable	1892 ab	1560 ab	2.0 a	1.5 a	61 b	65 b
Degrading	970 c	325 d	1.5 a	0.5 b	78 b	45 c
Degraded	85 d	167 d	0.6 b	0.2 b	210 a	25 d
Recovering	105 d	1420 b	0.7 b	0.6 b	89 b	43 c
lsd	570		0.7		55	14

[a]Values with the same letter were not significantly different ($p > 0.05$).
[b]Measured on 200,0.5 m^{-2} quadrats per paddock in 1993 and 1997.
[c]Determined from 100 distances between neighbouring plants, and 50 plant basal areas per paddock measured in 1997.

the inability of pool-scale measures to fully distinguish among these three divergent units, results of other experiments are reported on a concentration basis.

Experiment two

Significant paddock condition and location effects were noted for total soil C [condition MS = 3.8×10^7, error MS = 9.7×10^5, $F_{2,2} = 41$, $p < 0.05$; location MS = 3.2×10^6, error MS = 2.1×10^5, $F_{8,8} = 15$, $p < 0.01$], total soil N [condition MS = 1.4×10^5 error MS = 3.3×10^3 $F_{2,2} = 43$, $p < 0.05$; location MS = 7.3×10^5 error MS = 1.3×10^5, $F_{8,8} = 6$, $p < 0.01$] and roots-litter [condition MS = 87.0, error MS = 2.2, $F_{2,2} = 40$, $p < 0.01$; location MS = 38.2, error MS = 4.7, $F_{8,8} = 8$, $p < 0.05$] in the micro-patch analyses. No block (slope position) effect or interactions were noted between main effects for any of the characteristics. Concentrations of C (Figure 4a) and N (Figure 4b) were significantly higher on intact and degrading paddocks and different from degraded paddocks. Carbon levels on degraded paddocks (6567 mg g^{-1} soil) were 21% lower than in degrading paddocks (8279 mg kg^{-1} soil), and 30% lower than in stable paddocks (9254 mg kg^{-1} soil). Alternatively, N concentrations in soil of degraded paddocks (427 mg kg^{-1} soil) were 24% less than paddocks in degrading or stable condition ($\overline{X} = 575$ mg kg^{-1} soil). Root and litter concentrations (Figure 4c) were higher in intact paddocks (5.1 g kg^{-1} soil) than degrading or degraded paddocks (3.3 and 1.8 g kg^{-1} soil). Concentrations of all three properties were highest under and near tussocks, compared to the remaining locations across the space between plants (Figure 4). High concentration areas were more concentrated in intact paddocks. Average transect lengths for the sampled micro-patches were 55, 90 and 195 cm on the intact, degrading and degraded paddocks, respectively. No differences ($p > 0.05$) were noted in main or interaction effects on total soil P [$\overline{x}\delta$ (s.d.) = 95.2 (22.5) mg kg^{-1} soil].

Experiment three

Significant ($p < 0.05$) block and paddock condition main effects and unit × location interactions were noted in distribution of total soil C, as were paddock condition and unit × location interactions for total soil N (Table 5). Bottom-of-slope paddocks had higher overall total soil C than top-of-slope paddocks (8083 vs. 7425 mg kg^{-1} dry soil; lsd = 351) across treatments and locations. Intact and stable paddocks had the highest concentrations of soil C (9117 and 8891 mg kg^{-1} soil), followed by degrading (8400 mg kg^{-1} soil) paddocks (Figure 5a). Degraded and recovering State 2 paddocks had the lowest concentrations (6117 and 6450 mg kg^{-1} soil, respectively). As with soil C, the highest concentrations of total soil N were recorded in intact and stable paddocks (573 and 559 mg kg^{-1} soil) followed by degrading paddocks (502 mg kg^{-1} soil). Degraded and recovering paddocks had the lowest concentrations of soil N (373 and 401 mg kg^{-1} soil). Tussock centres had the highest concentrations (8730 mg C kg^{-1} soil and 531 mg N kg^{-1} soil), followed by up- and

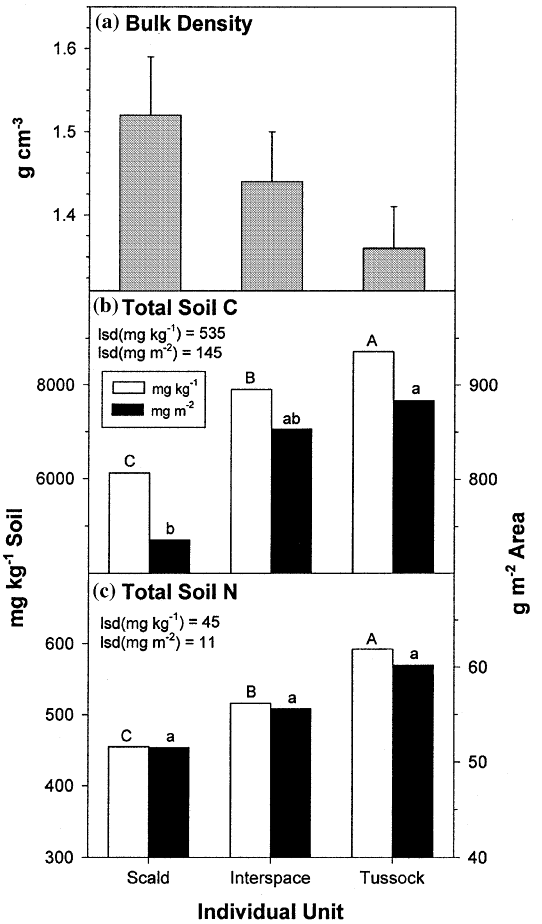

Figure 3. Comparison of differences in (a) soil bulk density (± 1 s.d.), concentration and pool-scale measurements of (b) total carbon and (c) total nitrogen of soils under different types of units found within patches of northern Queensland, Australia. Columns with the same letter (uppercase for concentration, lowercase for pool sizes) were not different ($p > 0.05$).

down-slope locations in proximity to tussocks (Figure 5b). Centres of bare interspaces had the lowest levels recorded (7010 mg C kg^{-1} soil and 425 mg N kg^{-1} soil). Total soil N had a clearer delineation among spatial locations than soil C, with significantly higher concentrations at tussock centres than other locations, and lower concentrations at centres of bare interspaces than other locations. The only significant effect noted on total soil P was location within units. Centres had higher concentrations (102 mg kg^{-1} soil) than upslope or down-slope positions (95 and 93 mg kg^{-1} soil, respectively; lsd = 5.4).

A significant ($p < 0.05$) interaction in concentration of roots and litter was noted between paddock condition, unit and location (Table 5). The highest levels were recorded at tussock centres of intact and stable paddocks, and the lowest levels within bare inter-spaces of degrading, degraded and recovering paddocks (Table 6). Tussock centres on degraded and degrading paddocks had amounts similar to up-slope and down-slope positions near tussocks in intact and stable paddocks.

Discussion

Biological activity (including plants), with its input of organic matter and effect on soil structure, is important to the maintenance of soil condition of grazing lands in the Australian tropics (Williams et al. 1993; Holt et al. 1996; Northup et al. 1999). Plants convert solar energy into plant tissues that are eventually converted to soil organic matter via decomposition, and provide constituents required for the maintenance of soil structure and nutrient cycles (Oades 1993). Our study confirms the existence of links between condition of grass tussocks and important soil properties in this silvopastoral system. Areas near tussocks had higher concentrations of soil C, N and plant materials than adjacent bare spaces across all grazing treatments and both grazing histories. Though accumulated grazing pressure did not cause large-scale changes in spatial distribution of total soil C or N around plants, the amount and range of values did change, as did plant size and spacing. Under heavy grazing, condition of high resource areas near plants were converted to those more similar to conditions noted in centres of bare spaces.

Studies in other semi-arid plant communities of Australia have reported that grass tussocks played key roles in landscape function and maintenance of soil condition. Ludwig et al. (1994) recorded higher concentrations of mineral N, soil C, and available P in the surface layers of soil in areas dominated by tussock grasses, compared to neighbouring bare patches. Northup et al. (1999) found enhanced soil microbial biomass within ± 8 cm of tussocks, which could be correlated to the higher concentrations of plant materials and nutrients we recorded near plants (e.g. improved nutrient cycling). Higher soil faunal activity and improved hydraulic properties have also been reported in tussock-dominated areas (Holt et al.

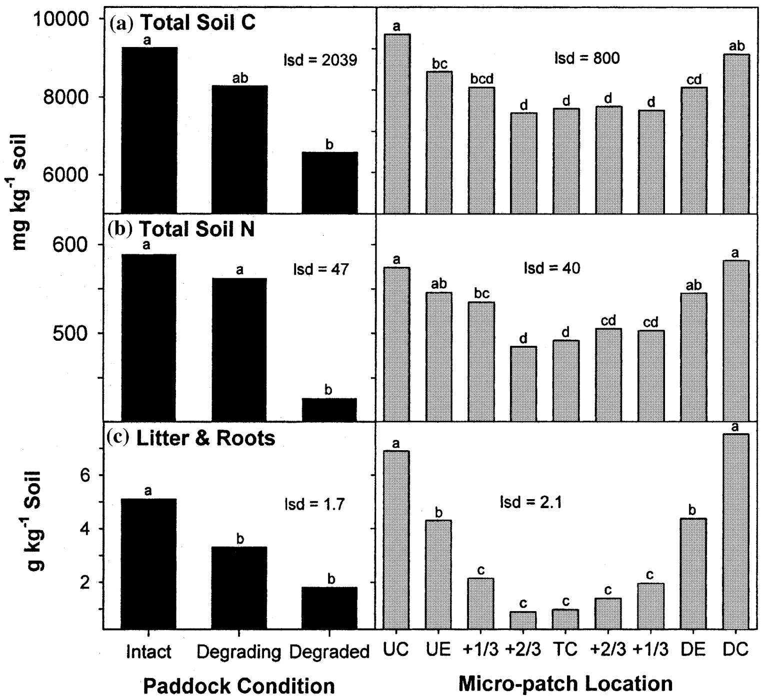

Figure 4. Effects of paddock condition and location within micro-patch on (a) total soil C, (b) total soil N and (c) soil-borne plant material (roots and litter) in a Red Chromosol soil. Columns with the same letter were not different ($p > 0.05$).

Table 5. Analyses of variance of paddock treatment, unit (grass tussocks and bare inter-spaces) within micro-patches and location effects on soil characteristics of a Red Chromosol soil in northern Queensland, Australia.

Source	d.f.	Total C		Total N		Total P		Roots & Litter	
		MS	*F*	MS	*F*	MS	*F*	MS	*F*
Block (A)	1	6.6×10^6	36.6*	26182	7.7	0.1	< 0.1	1.1	11.0
Treatment (B)	4	2.6×10^7	1444.0**	79192	23.2*	1322.0	0.9	32.4	324.0**
error a (A × B)	4	1.8×10^4		3411		1471.1		0.1	
Micro-unit (C)	1	2.2×10^6	4.6	2926	1.4	27.6	0.7	419.9	381.7**
B × C	4	2.9×10^5	0.6	1693	0.8	20.5	0.5	13.1	11.9*
error b (A × B × C)	4	4.7×10^5		2162		40.9		1.1	
Location (D)	2	3.6×10^5	0.7	2576	2.9	175.1	83.4**	39.1	195.5**
error c (A × D)	2	4.9×10^5		886		2.1		0.2	
B × D	8	1.4×10^5	1.0	514	1.2	56.8	0.5	0.6	6.0
error d (A × B × D)	8	1.4×10^5		436		114.2		0.1	
C × D	2	2.2×10^6	12.2**	5199	6.1*	133.7	2.0	46.0	153.3**
B × C × D	8	1.2×10^5	0.7	602	0.7	49.0	0.7	1.1	3.7*
error e	11	1.7×10^5		857		67.3		0.3	

*$0.01 < p < 0.05$
**$p < 0.01$.

1996), resulting in improved soil moisture conditions. Bridge et al. (1983) found that soil in areas with healthy populations of native grasses had higher (46%) root and litter mass than soils in bare scalds. Our study produced similar results in the comparison of resource concentrations near tussocks and in bare interspaces.

While amounts of soil resources around *B. ewartiana* tussocks were enhanced, this effect did not extend any appreciable distance into

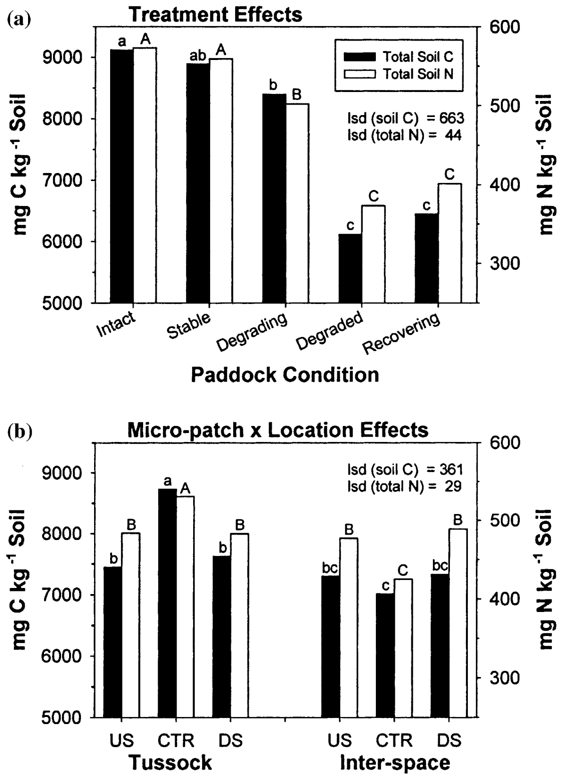

Figure 5. Effects of (a) paddock condition, and (b) unit within micro-patch × location interactions, on total soil carbon and nitrogen in a Red Chromosol soil. Columns with the same letter (uppercase for N, lowercase for C) were not different ($p > 0.05$).

neighbouring bare spaces. As such, the role of individual tussocks in the function of this landscape appears restricted to scales < 30 cm diameter. However, grass tussocks on this site were organised into different sized patches (up to 20 m diameter) across the landscape (Northup et al. 2003), both in spaces between trees and under tree canopies (Jackson and Ash 1998; Northup et al. 2005). As such, grass tussocks have broad collective impacts on soil condition, despite their small individual effects. The effect of other grass species on soil condition should be considered in future studies. Many species of tussock grass are present in eucalypt woodlands (McIvor and Gardener 1991), and their effects on soil condition have not been widely studied. *B. ewartiana* tussocks on sites used in these experiments had living basal area spread through 8–25 cm diameter areas, while *H. contortus* and *T. triandra* tussocks had 5–12 cm areas with live basal area (B. Northup, unpublished data). Northup et al. (1999) noted differences in soil microbial C among four species of tussock grass, apparently due differences in plant sizes. Therefore, it can be surmised that species-specific effects on local soil conditions likely exist.

Grazing regimes applied to the degrading and degraded paddocks appeared to impair the mechanisms by which landscapes in semi-arid Australia are hypothesised to conserve resources (Tongway and Ludwig 1997). On undegraded landscapes, herbaceous vegetation in the Australian tropics is largely organised in patches separated by areas with limited herbaceous growth (Ludwig et al. 1994; Tongway and Ludwig 1997). On our site, herbaceous cover was organised in patches (oriented cross-slope) 20–40 wide and up to 100 m in length (Northup et al. 2005). These patches were comprised of loosely arranged groups (or micro-patches) of tussocks that were also oriented cross-slope. As hypothesised by Tongway and Ludwig (1997), under relatively undisturbed conditions both individual and groups of tussocks within the larger bands interact with overland flow of water and nutrients (and litter) in runoff following storms. Runoff is generated in 'source' zones centred on

Table 6. Effects of paddock condition, unit within micro-patch, and location interactions on soil-borne plant material (roots and litter) of a Red Chromosol soil in northern Queensland, Australia.[a]

Paddock condition	Tussock (g kg^{-1} soil)			Interspace (g kg^{-1} soil)		
	US	CTR	DS	US	CTR	DS
Intact	7.1 cd	13.2 a	5.9 de	1.7 hjkm	1.3 km	2.4 ghjk
Stable	7.4 cd	12.9 a	6.8 cd	1.4 km	1.2 km	1.5 jkm
Degrading	3.7 ghj	7.5 b	3.7 fg	0.6 m	0.7 m	0.8 m
Degraded	1.5 jkm	5.2 ef	1.6 jkm	0.2 m	0.3 m	0.3 m
Recovering	4.8 ef	8.9 b	3.0 ghj	0.3 m	0.2 m	0.4 km

[a]Values with the same letter were not statistically different ($p > 0.05$); LSD = 1.52 g kg^{-1} soil.

non-vegetated areas upslope of run-on areas, after the surface layer of soil becomes saturated. As runoff moves through plant-dominated areas down-slope of a source area, grass tussocks act as small barriers, forcing the runoff to follow a sinuous path compared to movement across the bare spaces (Ludwig et al. 1994). The diffuse physical barriers presented by tussocks – in combination with locally improved hydraulic conductivity (Holt et al. 1996) – acts as small catchments, allowing some water and nutrients to infiltrate the soil, and deposition of litter and sediment on the surface. These captured resources enter soil pools and are used to generate pulses of biological activity, if they exceed levels that will trigger growth (Tongway and Ludwig 1997).

Grazing pressures applied to the heavily grazed paddocks interfered with this fine-grain mechanism by causing reductions in root systems and live basal area. Tussocks (and tillers within tussocks) died in response to the heavy grazing regimes, and surviving plants became smaller and more widely dispersed within paddocks. This response resulted in larger runoff zones, fewer interactions between runoff and plants, and reduced pools sizes available to generate plant and microbial activity (Ludwig et al. 1994). Soil bulk density also increases and hydraulic conductivity decreases under intense defoliation of grasses, due to loss of structure at the soil surface and organic matter (captured or produced) inputs (Bridge et al. 1983; Holt et al. 1996). Grazing pressures applied to the aggressively utilised paddocks in this study effectively caused an increase in leakiness of the landscape (Tongway and Ludwig 1997), with fewer resources 'captured' within the paddocks.

Declines noted in the heavily grazed paddocks were somewhat integrated and occurred rapidly (within 5 to 15 years). Grazing pressures applied to degrading and degraded paddocks reduced tussock basal area by 44 and 69%, respectively, and caused similar reductions in soil-borne plant materials. Total soil C and N were also reduced by 9, 31, 12 and 29%, respectively. Studies in temperate North American grasslands have generally reported that several decades were required before declines were noted (Derner et al. 1997), if at all (Henderson et al. 2004). The rapid responses we recorded were partially related to the general infertility of eucalypt woodlands (Williams et al. 1993; Tongway and Ludwig 1994). These plant communities are capable of functioning under drought and low soil fertility, as noted in the ungrazed paddocks. However, they lack the resistance (small basal areas and root mass) and resilience (low nutrient concentrations) required to function under heavy grazing (Ludwig et al. 1994; Tongway and Ludwig 1997). Further, the humid conditions that existed during the wet season likely had an effect, allowing rapid decomposition of the limited, and continually smaller, amounts of soil organic matter input by plants. Bridge et al. (1983) recorded levels of soil respiration of 610 g C m^{-2} y^{-1} on experimentally created scalds over 2 years, accompanied by a 46% reduction in roots and litter mass (to 30 cm depth), and 30–40% reductions in total soil C and N in surface layers. Similar responses have been noted in other herbaceous communities. Derner et al. (1997) found long-term (> 25 years) grazing of North American tallgrass and midgrass communities indirectly reduced soil C and N (23 and 18%, respectively) under *Schizachyrium scoparium* Michx. (Nash) tussocks by modifying the size class distributions of plants. Similar effects on plant-induced soil heterogeneity were noted for a North American shortgrass prairie (Vinton and Burke 1995). In contrast to the heavier grazing regimes, retention of soil and plant characteristics on the lightly grazed State I paddocks indicated grazing of eucalypt woodlands is sustainable, if grazing pressure is balanced against landscape productivity.

The localised tussock and micro-patch scale effects noted here were below the scales used to monitor grazed landscapes in Australia, normally paddock-scale measures for hundreds or thousands of hectares (Noble and Brown 1997). This dichotomy between landscape function and management decisions is problematic, given the heterogeneous organisation of north Australian landscapes (Brown and Ash 1996). Monitoring systems in northern Queensland should include measurements at the scales that most effectively capture information related to a disturbance (Noble and Brown 1997; Friedel et al. 2000). Herbaceous vegetation (and hence soil resources) in these communities is nested across multiple scales, ranging from individual tussocks, through groups of tussocks, to larger bands of vegetation (Northup et al. 2005). This pattern can be defined as being hierarchically organised, with finer-grained processes embedded and functioning within larger (coarser-grain) scales (Noble and Brown 1997). Fine-grained processes are generally considered inconsequential at coarser scales, except the most apparent characteristic(s). However, the most-apparent characteristics of fine-scale processes in our study were the limited amounts of plant and soil resources present, highly localised spatial distributions, and rapid responses to heavy grazing. As such, paddock-scale effects of grazing in northern Queensland could be effectively described at these smaller scales.

Variables used to define land condition should be chosen with care, as use of the wrong indicators could exacerbate the effects of disturbance. For example, paddock-scale responses of the recovering units indicated land condition could be misidentified if standing crop, which was similar to stable State 1 paddocks, were used. Alternatively, basal area and soil properties showed little improvement, indicating the paddocks were still in a degraded condition. Monitoring systems in northern Australia should include assessments of multiple characteristics and multiple scales to properly assess land condition. The method of presenting responses may also be important, as noted in the comparison of pool-scale and concentrations of soil nutrients (experiment one). Pool-scale measures are normally used to describe sequestration and spatial distribution of resources on a unit area basis. These measures are useful for developing resource maps or defining nutrient availability for a particular land use, but may have little correlation to soil condition or management effects. In this study, differences between units with the highest and lowest concentrations and bulk densities (tussocks and scalds, respectively) were relatively small (2500 and 137 mg kg^{-1} for total soil C and N, respectively; 0.16 g m^{-3} for bulk density). Further, responses of these characteristics exhibited a degree of negative correlation, with higher bulk densities noted in combination with lower nutrient concentrations. If used in defining the effects of grazing, this autocorrelation among variables could partially nullify the effects of management (Henderson et al. 2004). As such, pool-scale measures should be used cautiously in monitoring land condition.

Conclusions

Eucalypt woodlands in northeast Australia are highly susceptible to management-related disturbance. Evidence also suggests long – and economically non-viable – time periods will be required for State 2 land to recover from continuous heavy grazing (Brown and Ash 1996). When grazed, the best strategy for management of eucalypt woodlands is to balance stocking rates against ecological and climatic constraints and prevent damage from occurring. In this study, the most sustainable management included conservative stocking rates and wet season deferment of grazing.

Responses noted in this study were indicative of the coupling that exists between disturbance, biological responses and soil properties across northern Australia (Williams et al. 1993; Tongway and Ludwig 1997; Northup et al. 1999). They also highlight the need to describe grazing effects across multiple, especially finer-grained, scales to identify transitions to less-productive states (Noble and Brown 1997). Condition of grazed landscapes in northern Australia should also be monitored with combined plant and soil indicators to better identify such changes (Whitford et al. 1998). The best choices for indicators would be those that are easy to measure and insensitive to annual variations in growing conditions, but still sensitive enough to allow early identification of degradation (Northup et al. 2003). Herbaceous basal area, soil-borne plant materials, and total soil N could provide useful combinations for sites with Red Chromosol soils. All are relatively easy to describe, important to land condition, and sensitive to disturbance by grazing.

Acknowledgments

Data used in this manuscript were collected from experimental paddocks that were part of the Meat and Livestock Australia (MLA) funded project NAP 3.205. The authors would like to thank Mr and Mrs C. Ferguson for the use of land on Cardigan Station, Dalrymple Shire, Queensland, and staff of the Soil Analytical Laboratory, CSIRO Davies Laboratory, for their assistance in completing soil analyses.

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