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Decline in grazing land condition in the Northern Gulf region of Queensland 1990–2018

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ABSTRACT

The cattle industry in the Northern Gulf region of Queensland, Australia, is based primarily on extensive grazing of native pastures on pastoral leasehold land. Large leasehold areas managed by few people make maintaining rangeland productivity and landscape function difficult for land managers. Seventeen discreet land types were identified and assessed across the Northern Gulf region over three periods (2004 [260 sites], 2012 [260 sites] and 2016 [252 sites]) to derive regional trends in rangeland condition. Further, detailed data from Queensland state-government QGRAZE sites (1992–2018) were analysed to assess long-term land condition changes on identified 'at risk' land types. Land condition attributes monitored included woodland thickening, pasture composition, soil surface condition and exotic weed incidence. Last, remote sensing was used to analyse woody cover dynamics across 23 regional land types and 30 QGRAZE sites from 1990 to 2018. Combined, analyses showed continued land condition decline across the region. Since 2004, the proportion of retained original carrying capacity is estimated to have declined from 72% to 66%. Land condition of high-value land types was slightly lower than that of low-value types. Estimates suggest that 50% of original carrying capacity will be lost by 2046 if current land condition trends continue, with the primary degradation factors being loss of preferred pasture species and woodland thickening. These results are possibly replicated in other extensively grazed regions of Queensland; however, lack of objective data suggests the need for an expanded monitoring program and a concerted response to address continuing land condition decline. The recommended hybrid monitoring methodology, including historical data, rapid assessments and remote sensing is low-cost, and could effectively be implemented elsewhere to show land condition change without needing to collect management information. Remediation will not be possible without the active engagement of industry, government and agencies. Effective management practices are discussed.

Keywords: carrying capacity, grazing management, pasture composition, rangeland condition, remote sensing, soil erosion, stocking rates, weeds, woodland thickening.

Introduction

In Queensland, Australia, rangeland condition (defined here as the capacity of a land type to respond to rainfall and produce useful forage) has declined on grazing land in 'Cape York' (Neldner *et al.* 1997), the Northern Gulf (Shaw *et al.* 2007), and the Burdekin and the Fitzroy River catchments (De Corte *et al.* 1994; Karfs *et al.* 2009) (Fig. 1). However, whereas trends in land condition and viability issues are assessed and reported over time elsewhere (e.g. Novelly and Warburton 2012; Department of Agriculture and Food, Western Australia 2017), no such ongoing assessments have been made for Queensland rangelands.

Pastoral leasehold land occupies 44% and 62% of Australia and Queensland respectively (Australian Trade and Investment Commission (Austrade) 2008) and should be

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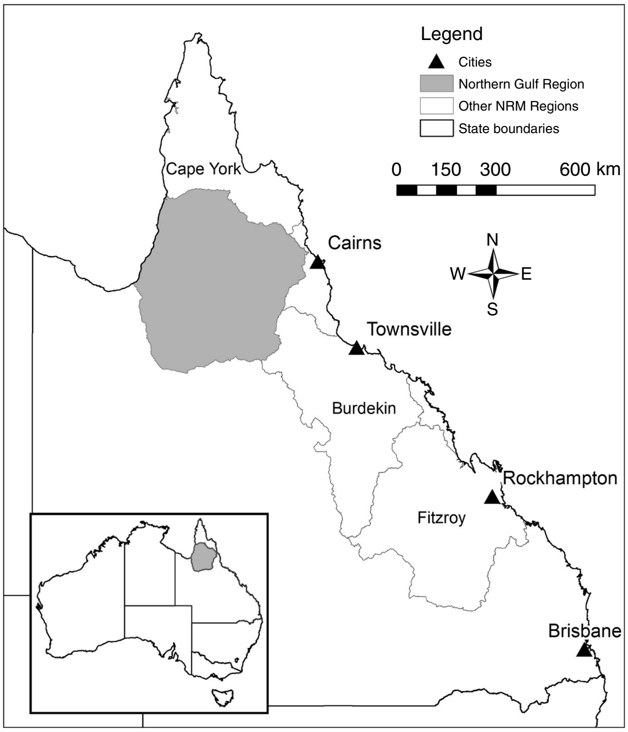

Fig. 1. Location of the Northern Gulf region and some adjacent regions in relation to the state of Queensland.

maintained in good or at least fair productive and environmental condition. However, in assessing condition, a key problem is lack of long-term on-ground data to support largely anecdotal evidence of land condition decline. Although such anecdotal evidence has encouraged Governments to spend hundreds of millions of dollars on projects supporting improved resource management over the past 30+ years, there is little evidence of positive on-ground outcomes.

Effective rangeland monitoring must incorporate the herbaceous layer, any tree and shrub layer, and the soil (Friedel 1991). Monitoring and maintaining rangeland productivity and landscape function is challenging for both land managers and government agencies, owing to the following: the characteristically vast, sparsely populated areas; limited infrastructure; a complex relationship between vegetation dynamics, management, production and profitability responses in a variable climate; and gradual landscape changes over decadal time scales. For example, by 1961, the desirable (for livestock) kangaroo grass (*Themeda triandra*) in northern Queensland was rapidly declining through overgrazing under the extensive grazing systems then employed (Anon. 1961), being replaced by black speargrass (*Heteropogan contortus*). Subsequently, black speargrass had itself been depleted, replaced by Indian couch (*Bothriochloa pertusa*) (Spiegel 2016), particularly in the Burdekin River catchment (McKeon *et al.* 2004).

Few monitoring projects across northern Australia have been at a landscape level, with no long-term objective monitoring programs assessing land condition trends in the grazed rangelands of Queensland or the Northern Territory. The most recent assessment of northern Australia land condition before 2000 was by Tothill and Gillies (1992), a desktop study collating regional expertise. This described land condition across plant communities (largely derived from Weston *et al.* (1981)) as either A (sustainable), B (deteriorating) or C (degraded), by using a matrix based on soil condition, vegetation condition and management capability. At that time, only 30% of the northern black speargrass lands (includes the eastern half of the Northern Gulf region) were described as in a sustainable condition, with 55% deteriorating, whereas 75% of the *Aristida–Bothriochloa* lands (includes the western half) were in a sustainable condition, with only 15% deteriorating. The major components were exotic weeds, pasture species decline and woodland thickening.

Initiated in 1989, the QGRAZE project of the Queensland Department of Primary Industries (DPI) was designed to objectively monitor 'at-risk' landscapes by using a common methodology over a 30-year period, and attempt to quantify whether the conclusions of Tothill and Gillies (1992) were factual, and current throughout Queensland. QGRAZE sites were to be photographed annually, and intensively assessed for pasture composition, ground cover and tree basal cover at 5-yearly intervals. By 2001, 441 sites were established across Queensland, with 30 in and adjacent to the Northern Gulf region (~20 million ha) (Fig. 2). In the early 2000s, QGRAZE was defunded, and funds were redirected to catchment based Natural Resource Management (NRM) groups. Rangeland monitoring throughout Queensland became *ad hoc* or was abandoned. However, the Northern Gulf Resource Management Group (NGRMG) and northern DPI Beef Extension staff continued to track land condition trends using simplified recordings on those 30 QGRAZE sites located in or near the Northern Gulf region. In 2003/2004, the monitoring area was broadened to the entire Northern Gulf region through a rapid appraisal survey methodology.

Whereas QGRAZE examined 'at risk' land types, the rapid appraisal survey of a separate 260 randomly-selected sites was conducted to provide an overview of land condition across the Northern Gulf (Shaw *et al.* 2007). By using the ABCD land condition framework (Chilcott *et al.* 2003), which assesses soil condition, pasture composition, weed infestation and woodland density, land was described as either A ('good'; 100% of original carrying capacity), B (75% of original carrying capacity), C (45% of original carrying capacity) or D ('poor'; 20% of original carrying capacity) condition. Across all land types, 47% of assessments were A condition, 34% B, 17% C and only 2% in D condition. At that time, 14 broad land types were recognised and assigned a relative grazing value from 10 (highest) to 1 (lowest) on the basis of producer understanding of the livestock productive capacity of the land type (Kernot 1998)

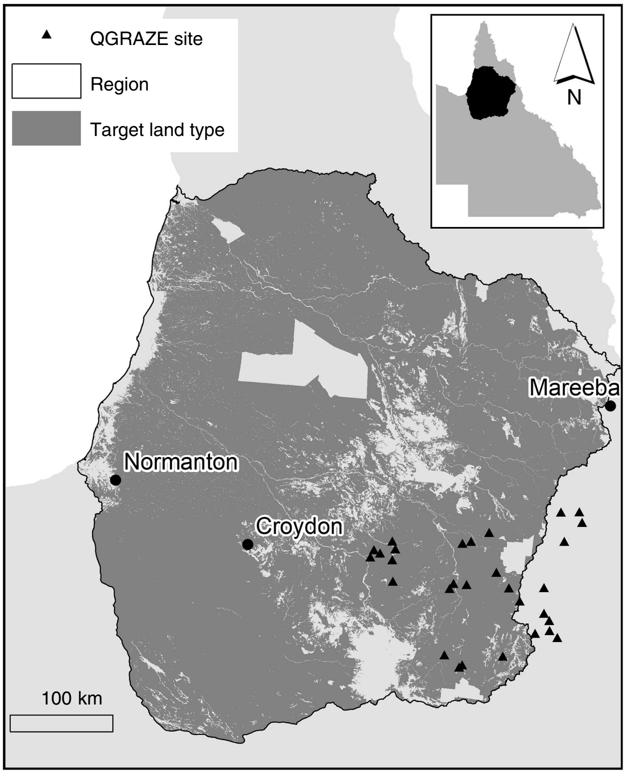

Fig. 2. The location of regional land types and QGRAZE sites where 'Persistent Green' data were analysed in the Northern Gulf region.

Table 1. Number of sites assessed for each land type across the Northern Gulf region, together with the relative grazing value of each type (highest grazing assigned the value 10).

Land type	Grazing value	2004	2012	2016
Alluvial soils	10	18	17	17
Black soil	9	16	17	15
Marine plain[A]	8	1	1	1
Red basalt[A]	7	8	1	1
Red duplex	7	30	15	15
Limestone[A]	7	2	2	2
Georgetown granite	6	11	7	6
Other granites	6	8	11	11
Old alluvial	6	21	20	20
Bluegrass/Browntop	6	0	6	4
Red earth	5	36	27	26
Duplex	4	0	17	17
Yellow earth	3	56	58	58
Sandy forest	1	18	33	33
Sand ridge[A]	1	6	3	2
Range soil	0.7	23	20	18
Lancewood	0.5	6	5	5
Total		262	260	251

[A]Land type excluded from analysis because of low occurrence or coverage during the rapid assessments.

(Table 1). In all, 75% of high grazing-value land types (grazing value of >5) were in A or B condition, whereas 88% of low grazing-value land types (grazing value of ≤5) were in A or B condition. However, some important high-value land types were badly degraded. Georgetown granites had only 27% of sites in A or B condition, alluvials 59%, black soils 64% and red duplex soils 57%.

The Shaw *et al.* (2007) data for the Northern Gulf region assessed land condition as declining, mainly because of pasture composition and timber thickening, indicating the major driver was overstocking (diet selection, lack of fuel for burning, and exclusion of fire). Since the 1920s, cattle numbers have increased (Irvine *et al.* 2025; Fig. 3), with more internal fencing, artificial waters and urea supplementation.

This paper describes changes in grazing land condition from on-ground and remotely sensed monitoring across the Queensland's Northern Gulf region over a period of about 30 years. The rapid appraisal survey conducted in 2003/2004 was repeated in 2011/2012 and 2015/2016. We integrated the results of these rapid appraisal field surveys, QGRAZE project assessments, and remotely sensed woody vegetation cover datasets to corroborate the field results and better inform analysis of land condition trend. The results could be used to shape the direction of public (government) investment in resource management to address priority areas. Finally, potential mechanisms for arresting land condition and productivity decline and advocating for rangeland restorative practices are discussed.

Methods

Study area

The Northern Gulf region of Queensland (Fig. 1) covers 194,000 km^2, with a total cattle herd of ~910,000 turning off ~246,000 head annually. Shaw *et al.* (2007) described the land systems, climate and extensive beef production systems. Beef production across 180 beef businesses is predominantly based on native pastures, with grazing land carrying capacities ranging from 4 to 30 ha per adult equivalent (AE = 450 kg steer at maintenance).

The region typically experiences a 4-month wet season (December to March inclusive), and 8-month dry season. A rainfall gradient runs approximately north–south, with average annual rainfall ranging from 1200 mm (CV ≈ 29%) in the north to 500 mm in the south (CV ≈ 41%). The duration of this study (1990–2020) included three dry periods (1992/1993–1995/1996, 2002/2003–2006/2007 and 2012/2013–2014/2015), and two wet periods (1996/1997–1999/2000

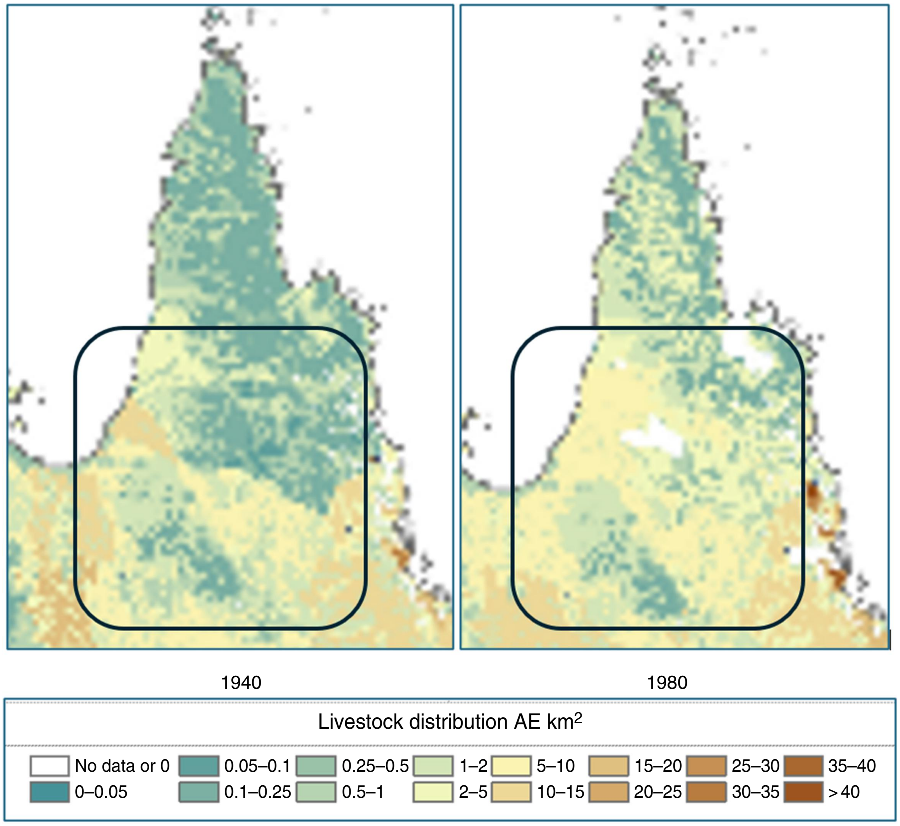

Fig. 3. Change in livestock density in the Northern Gulf region from 1940 to 1980 (Irvine et al. 2025).

and 2007/2008–2011/2012). Rainfall from 1980 to 2018 in key locations is presented in Fig. 4.

This study incorporated analyses of three separate datasets derived from 30 QGRAZE sites, 250–260 rapid assessment sites and 28 years of remotely sensed woody canopy cover data respectively (Fig. 5). Separate details on each analysis are provided below. The QGRAZE site selection was based on the land types of Perry (1964) and Galloway et al. (1970), whereas the rapid assessment and remote-sensing analyses used the more recent Grazing Land Management (GLM) land types (FutureBeef 2019).

QGRAZE

We assessed change on 30 QGRAZE sites on productive but at-risk of overgrazing (preferred by livestock) land types established between September 1991 and August 1995 in and adjacent to the region (Fig. 2). Sites were placed to encompass a range of soil types and productivity levels, with sites distributed on soil type as follows: Georgetown granites (7), red duplex (7), sandy granite (3), yellow duplex (3) and other soils (10). While the watercourse 'Frontage' land type was identified as 'at risk', it was excluded from the project because of general weed invasion and range condition collapse from overutilisation of preferred species. Each QGRAZE site consisted of a pegged 1-ha plot in which 3 × 100 m transects, 50 m apart, were established. Site photographs and transect measurements recorded pasture composition and yield (using BOTANAL, Tothill et al. 1992), ground cover and tree basal cover. Twenty 0.5 × 0.5 m quadrats were assessed from each transect. At the beginning of each sampling period, five standard quadrats were selected, representing the forage yield range anticipated for all assessments. At the conclusion of each sampling period, 10 quadrats were assessed for yield, cut, dried and weighed to establish regression equations for each assessor, which are then used by the BOTANAL program to establish total and individual species dry-matter yield and frequency distribution of all species recognised. All sites were measured at least twice between 1991 and 1999. Full QGRAZE assessments were discontinued in 2000, and replaced by 3–5-yearly rapid ABCD land condition assessments and site photos of the same sites. At least four land condition assessments were completed across the QGRAZE sites from 2006 to 2018. The historical management of these sites was not sought as part of this project.

QGRAZE analyses used generalised linear mixed-effects regression modelling. This allowed assessment of temporal trend in dependent variables, while accounting for within-site variance. We tested for trends in eight continuous variables: land condition, tree basal area, pasture yield, ground cover, soil surface condition, pasture composition, thickening, and weed discounts. Additional analyses were conducted for the application/absence of each of the four

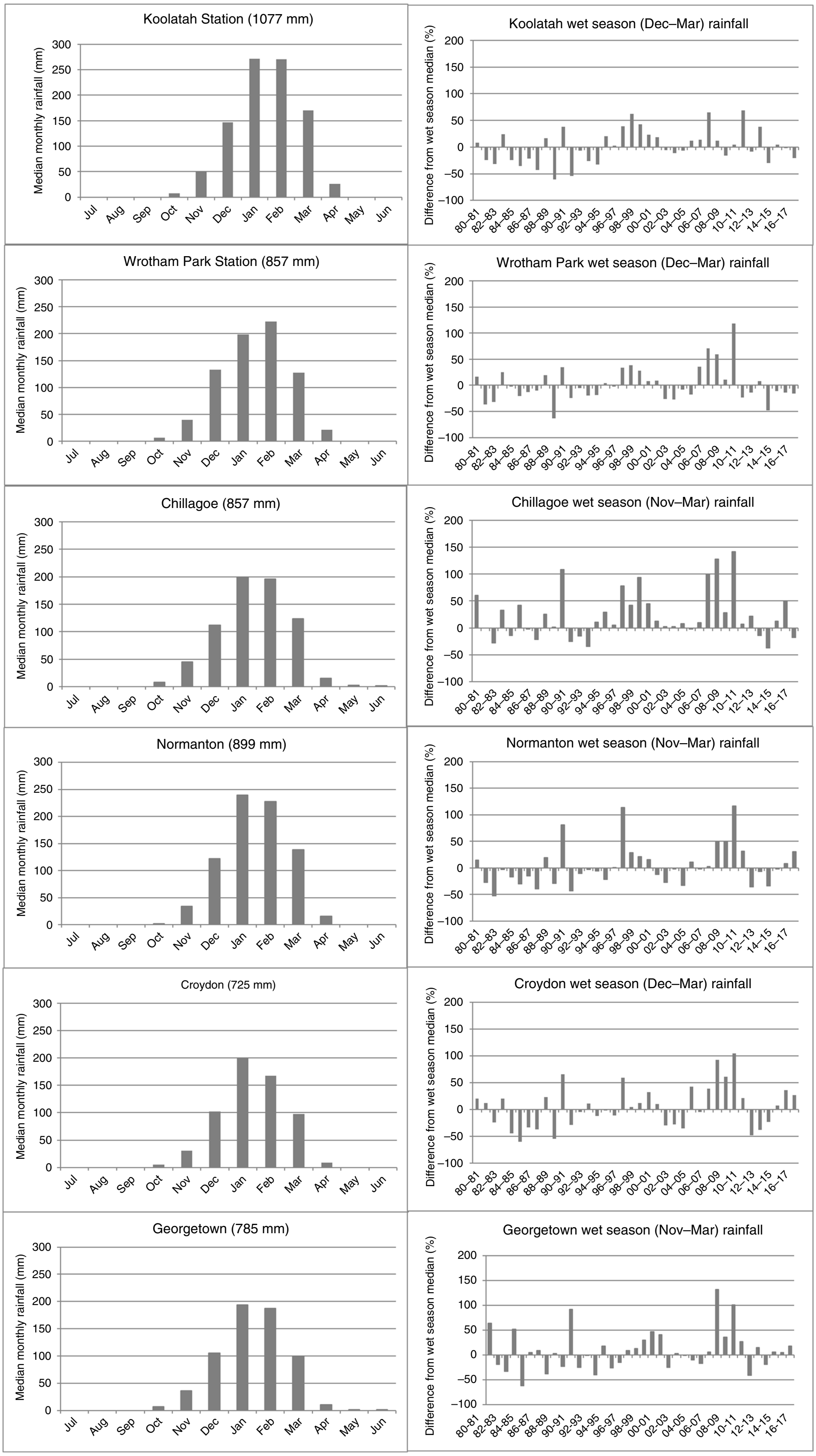

Fig. 4. Median monthly rainfall, and wet season rainfall for various regional sites from 1980 to 2018 expressed as the difference (%±) from the median for that period.

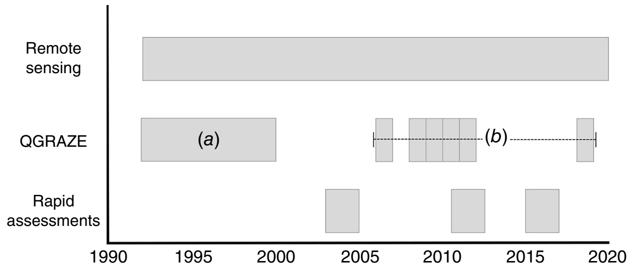

Fig. 5. A timeline showing the remote sensing, QGRAZE and rapid assessment periods. (*a*) Initial QGRAZE monitoring included detailed site transects and BOTANAL sampling, whereas (*b*) the ABCD land condition framework was the basis of subsequent QGRAZE assessments.

land condition discounts in the assessment by using logistic mixed-effects models, which are suitable for dichotomous outcomes. These analyses test for temporal trends in the probability of each discount being applied. Finally, we used logistic mixed-effects models to model the presence of the eight most common pasture species recorded in QGRAZE monitoring (>25 observations).

Rapid assessments

The 14 regional land types described by Shaw *et al.* (2007) were subsequently expanded to 17 as improved mapping became available (Queensland Herbarium 2024). Grazing values were assigned on the bais of vegetation, soil and production characteristics (Table 1). Assigned grazing values give the highest value (10) to the most productive land type, with other land types being rated as a relative value against that best type. Four land types (red basalt, sand ridge, marine plains and limestone) were excluded from the analyses because of limited occurrence, or low coverage in the assessment.

As for Shaw *et al.* (2007), and to remove any potential bias, rapid assessment teams were trained in site selection, land type recognition, land condition ratings, and estimated percentage of carrying capacity retained. The method relies on observers having some experience in a region and each result is an agreed value among observers. To facilitate analysis, the rapid assessments followed Shaw *et al.* (2007) in assigning a numeric retained long-term carrying capacity value to each condition rating. Each site was assigned one of seven land condition scores. 'A' condition indicates 100% of the original carrying capacity retained, 'A−' (87.5%), 'B' (75%), 'B−' (60%), 'C' (45%), 'C−' (32.5%) and 'D' (20%). Scores <100% indicate that a productivity discount has been applied for one or more of the woodland thickening, soil surface, weed encroachment or pasture composition parameters. We recorded which of these discounts were applied in each assessment.

The 'rapid land condition assessment' methodology differs profoundly from Chilcott's land condition assessment (Chilcott *et al.* 2003), which states that 'A' land condition is dominated by 3P pastures, and with no timber thickening, weeds or soil surface degradation. The 'rapid land condition assessment' methodology acknowledges that for some land types, the original state was dominated by increaser species and annuals, whereas other land types were dominated by trees, had sparse ground cover and poor surface soil characteristics. These land types were assessed as retaining 100% of its original carrying capacity ('A' land condition), with no discounts applied.

The rapid assessments required approximately 10 min per site, were predominantly adjacent to roads, and recordings comprised a site photograph, site coordinates, dominant tree species, weed infestations, tree basal area (Bitterlich point sampling (Bitterlich 1976)), and the top five ground cover species, as well as the proportion of each and ground cover percentage. Photo standards developed by the rapid assessment team were used to assess dry-matter yield. Land condition was assessed by considering each of the potential discounts against our understanding of the original condition for that land type. However, species contribution to yield was not included in the 2004 assessments.

Assessments were completed on three occasions and were designated as follows: (i) the 2004 assessments (Shaw *et al.* 2007) on 262 sites in 2003 and 2004, (ii) the 2012 assessments between May 2011 and June 2012 on 260 sites, and (iii) the 2016 assessments between April 2015 and June 2016 on 250 sites (Table 1, Fig. 6). The original 2004 assessment sites were selected using a combination of distance from the previous site and change in land type. Other sites were identified prior to the 2012 assessment to better represent the mix of land types, and some existing sites from 2004 were eliminated. There were 122 sites common to all three assessment periods. The historical management of these sites are unknown.

Remote sensing

Woody vegetation cover analysis

To gauge long-term trends in woody cover, we assessed persistent green (PG) cover dynamics across the study region as a proxy. PG cover is a remotely sensed cover product based on Landsat imagery that seasonally estimates the portion of vegetation that does not completely senesce within a year, and which primarily consists of a combination of stem density and leafiness of trees and shrubs. (https://geonetwork.tern.org.au/geonetwork/srv/eng/catalog.search#/metadata/dd359b61-3ce2-4cd5-bc63-d54d2d0e2509). It is the only long-term woody cover time series available for the study region. PG measures foliage projective cover (FPC), the expanse of green leaves, not necessarily the number or size of woody stems. Crowley and Murphy (2023) demonstrated that FPC can change without any change in woody density, but they analysed autumn PG, which measures FPC after a full wet season

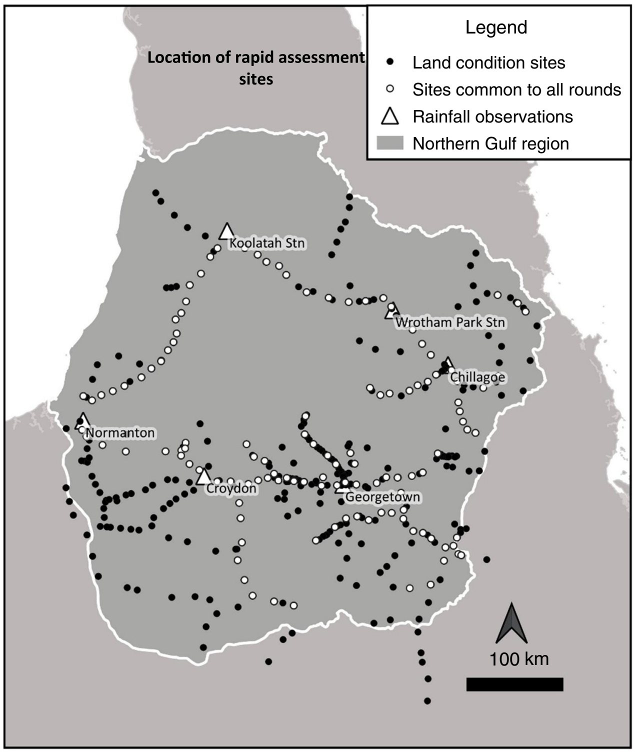

Fig. 6. The rapid assessment sites across the Northern Gulf region over the three assessment periods. The sites common to all three assessments are highlighted as are the sites of weather station data.

of growth. For this analysis, we used spring PG values to track mean annual PG values that relate to the end of the annual 7–8-month dry season, when annual leaf drop would have been near complete. Eucalypts can lose up to 40% of their leaves towards the end of the dry season (O'Grady *et al.* 2000).

Our analysis of PG dynamics covered 23 regional land types (FutureBeef 2019) that were either economically important or extensive within the study region (Table 2). These land types account for the majority of the region's grazing land, and provide a spatial analogue for the 17 land types identified in the rapid assessments. Note that these two sets of land type differ. Spatial land type mapping was not available for the early Rapid Assessments, and the land types used then were descriptive classes based on local expertise (Shaw *et al.* 2007). By contrast, the PG analysis was retrospective of all other work and required spatialised land type mapping, so the Grazing Land Management regional land types (FutureBeef 2019) were used for these analyses. However, the two sets of land types would cover the majority of regional grazing land and overlap extensively.

Using GIS software, we mapped 1000 random points in each of the 23 land types and 200 random points on each QGRAZE site. At each point, we then extracted annual (spring, 1992–2020) PG pixel values, and averaged these within each year and land type/QGRAZE site, to determine the average annual spring PG value for that land type in that year. For each land type and QGRAZE site, we then regressed average annual spring PG on year to detect any significant linear trends in PG over time. The Prais–Winsten method was used to estimate regression coefficients because it is appropriate for serially correlated data (Wooldridge 2008). Significant trends are interpreted here as indicative of trend in woody cover over time.

Table 2. Regional land types used in remote-sensing woody cover analyses, with respective grazing areas.

GLM land type	Area (km^2)
Sandy forest (NG13)	49,256
Range soil (NG08)	21,903
Sand ridge (NG12)	19,784
Narrow-leaved ironbark shallow soil (BD15)	11,884
Coolibah country (NG02)	8013
Bluegrass browntop plains (SG02)	7995
Frontage (NG03)	7885
Old alluvials (NG07)	7585
Ranges (BD16)	7143
Georgetown granites (NG04)	5942
Sandy forest country (SG13)	5250
Frontage (SG04)	3930
Red basalt (BD17)	1679
Narrow-leaved ironbark deep soils (BD14)	1563
Yellowjacket with other eucalypts (BD20)	1434
Loamy alluvials (BD13)	1301
Black basalt (BD01)	657
Yellow earths (NG14)	564
Goldfields country – red soils (BD11)	354
Downs (BD09)	334
Mitchell grass (SG) (SG10)	274
Marine plains (NG06)	167
Red earths (NG11)	167

Alpha-numeric text in parentheses indicates the Grazing Land Management land-type code.

Results

QGRAZE

The ABCD assessments from 2006 to 2018 across key QGRAZE sites showed no overall land condition decline during this period, with the red duplex and other soils remaining in B condition, whereas Georgetown granites

Table 3. Site variables and the strength of their temporal trend across the QGRAZE sites during the study period.

Variable	Period	Observations	*T* (*P*)
Condition score	2006–2018	93	-0.91n.s.
TBA	1994–2018	134	8.79***
Yield	1993–2018	158	0.71n.s.
Ground cover	2006–2018	93	-2.35**
Soil discount	2006–2018	93	-3.03**
Pasture discount	2006–2018	93	-1.39n.s.
Thickening discount	2006–2018	93	-1.39n.s.
Weeds discount	2006–2018	93	2.30**
Black speargrass (*Heteropogon contortus*; 3P)	1993–2018	162	-0.01n.s.
Wiregrass (*Aristida*; 1P)	1993–2018	162	3.56***
Indian couch (*Bothriochloa pertusa*; 2P)	1993–2018	162	5.39***
Bluegrass (*Bothriochloa*; 3P)	1993–2018	162	-2.04*
Kangaroo grass (*Themeda triandra*; 3P)	1993–2018	162	-0.34n.s.
Goldenbeard grass (*Chrysopogon fallax*; 3P)	1993–2018	162	-1.53n.s.
Seca stylo (*Stylosanthes scabra*; 3P)	1993–2018	162	3.73***
Pitted bluegrass (*Bothriochloa decipiens*; 2P)	1993–2018	162	3.78***

Significance of the trend (T) indicates the direction and significance of the time term in the respective model.
P-values: n.s., not significant; *$P < 0.05$; **$P < 0.01$; and ***$P < 0.001$.

remained in C condition. However, several significant temporal trends in recorded variables were identified, with tree basal area increasing and ground cover decreasing. Among land condition discounts, only the likelihood of weed and soil surface condition discounts changed significantly (increasing) over the study. Other notable changes were in occurrence of pasture species, with desirable (3P) (Chilcott *et al.* 2003) bluegrasses (*Bothriochloa* spp.) declining, whereas wiregrass (*Aristida* spp.), Indian couch (*Bothriochloa pertusa*), Seca stylo (*Stylosanthes scabra*) and pitted bluegrass *(Bothriochloa decipiens)* all significantly increased (Table 3).

The contradiction that land condition showed no overall decline, whereas component land condition indicators did decline may be partly explained by the following: (1) tree basal area and pasture species changes were measured over 24 and 25 years respectively, compared with only 12 years for land condition; and (2) the negative changes found in the QGRAZE sites may not have been great enough to trigger a change in ABCD land condition scoring, where differences

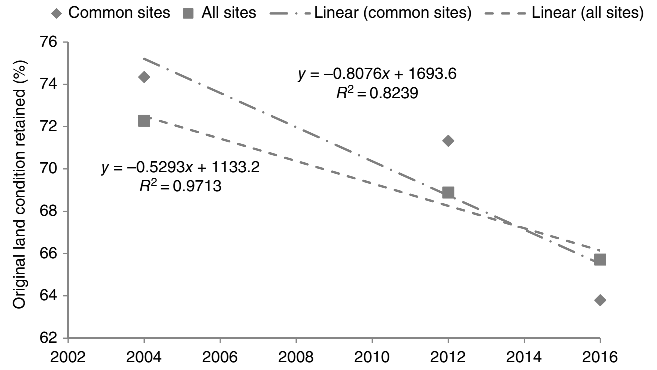

Fig. 7. Change in land condition across 'common' and 'all' rapid assessment sites over time expressed as the percentage of original land condition (100%) that has been retained at each assessment period.

between the classes range from 25% to 30% of original carrying capacity.

Rapid assessments

Carrying capacity

The overall change in the condition of the rapid assessment sites across all land types between 2004 and 2016 is expressed as the percentage of original land condition retained at assessment. These changes are shown for sites common to all three assessments, along with the means for all sites across the three assessment periods. For the common sites, 74% of the original carrying capacity was retained in 2004, but progressively declined to 64% by 2016. This closely mirrors the trend for all the rapid assessment site data at each assessment that had shown carrying capacity decline from 72% to 66% (Fig. 7). Similarly, there was no difference in results between 'common' and 'all' site data in any other parameter measured. Hence, for simplicity, only the 'all' site data are subsequently presented and discussed.

Land types were aggregated into high and low grazing value, and grazing and/or grazing management affected the land condition of all land types. There were 112, 95 and 90 sites included in high-value types (grazing value of >5) in 2004, 2012 and 2016 respectively, and 147, 165 and 161 sites in the low-value land types (grazing value of ≤ 5) over the three assessments. Overall, from 2004 to 2016, retained carrying capacity of high- and low-value land types declined from 71% to 67% and from 74% to 67% respectively (Fig. 8).

Condition and productivity discounts

Pasture composition discounts were applied to 78% of all site assessments. Tree thickening, soil surface condition, and weed land condition discounts were applied to 50%, 37% and 20% of assessments respectively. In 2004, 193 of the 260 rapid assessments (74%) were discounted because of

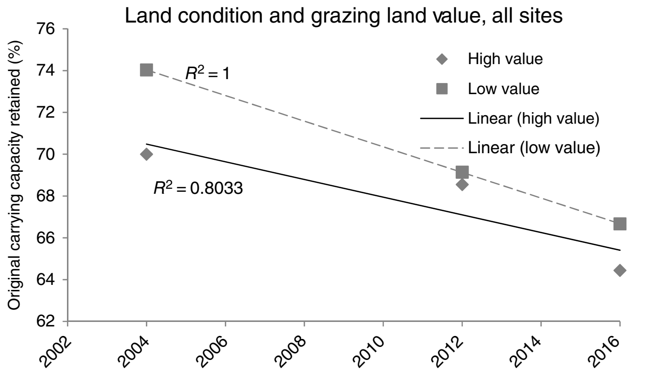

Fig. 8. Change in proportion of original carrying capacity retained at the three rapid assessment times for high grazing-value land types (grazing value of >5) and low-value land types (grazing value of ≤5).

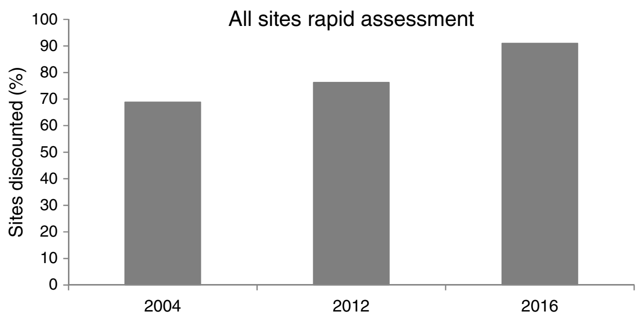

Fig. 9. Percentage of sites across each rapid assessment period, to which a land condition discount has been applied.

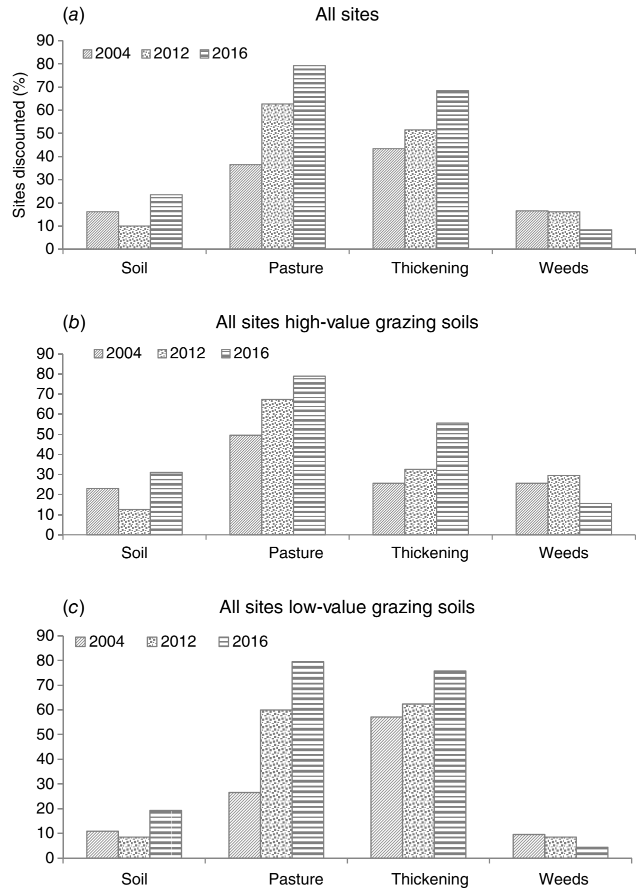

Fig. 10. Percentage of sites discounted for each category at each assessment for (*a*) all rapid assessment sites, (*b*) high grazing- value (GV > 5) land types, and (*c*) low grazing-value (GV ≤ 5) land types.

one or more of deterioration of soil condition, pasture composition, tree thickening or weed invasion. In 2012, this had increased to 80% of sites discounted and, in 2016, 90% of sites had been discounted (Fig. 9).

Considering discounts across each rapid assessment period for all sites (Fig. 10*a*), discounts for declining soil surface condition or weed invasion were relatively low (never above 24% of sites) compared with other discounts. Discounts for loss of pasture condition increased from 37% in 2004 to 79% in 2016, whereas those for timber thickening increased from 43% in 2004 to 68% in 2016. These data were further divided into land types of low and high grazing value. Data from all sites for each assessment on high and low grazing-value land are shown in Fig. 10*b*, *c* respectively. There was minor change in soil surface condition or weed invasion categories across the assessment periods, but there were incremental increases in discounts for pasture composition and timber thickening. For high-value grazing lands, discounts for pasture composition increased from 50% to 79%, whereas for timber thickening, discounts increased from 26% to 54% between 2004 and 2016. For low-value grazing lands over the same period, discounts for pasture composition increased from 27% to 80%, whereas, for timber thickening, they increased from 57% to 76%.

The average percentage discounts across the three rapid assessment periods for high grazing-value land types for all sites were 24%, 73%, 38% and 24% for soil surface condition, pasture composition, timber thickening and weed invasion respectively. For low-value grazing land types, the average percentage discounts were 11%, 55%, 65% and 7% for the respective categories. The mean basal area of woodlands increased from 4.3 to 5.8 m^2/ha from 2004 to 2016. The mean woodland density for low grazing-value land types increased from 4.9 to 6.5 m^2/ha, whereas high grazing-value land types increased from 3.5 to 4.9 m^2/ha (Fig. 11) over the rapid assessment period.

A 26-year photo sequence (1992–2018) from one particular site graphically portrays the rate and effect of timber thickening occurring in the Northern Gulf region (Fig. 12).

Remotely sensed woody cover

The remotely sensed woody cover analysis indicated a strong upward trend in woody cover across the region. All 23 regional land types showed a significant ($P < 0.01$) upward trend in mean annual persistent green (PG) values and, based on the modelled slope coefficients in each land

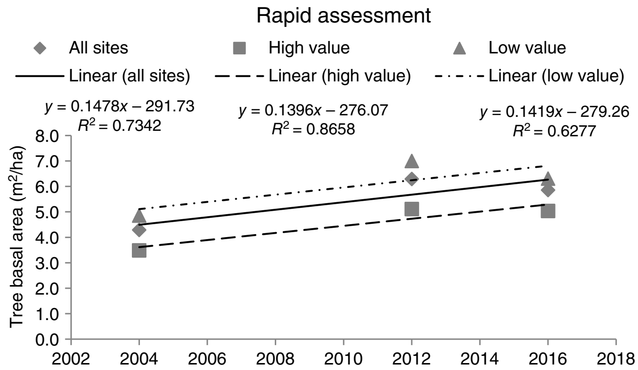

Fig. 11. Change in mean tree basal cover over the three rapid assessment periods for all sites as well as high grazing-value and low grazing-value land types.

type, these equate to changes per land type between 4.2% and 12.8% in woody cover over the study period (Table 4).

Results of woody cover analyses of the 30 QGRAZE sites were similar to those of the regional land types, although less emphatic. In total, 21 sites had a significant ($P < 0.05$) upward trend in mean annual PG, equating to an estimated change in woody cover of between 4.7% and 16.0% (Table 5). No sites showed a significant downward trend.

Discussion

Rainfall over the period

Rainfall was generally split 50:50 or better between above and below median wet season totals (Fig. 4). Inter-annual rainfall variability is a normal feature of semi-arid landscapes in northern Australia, and should be accounted for in stocking decisions as a normal part of land management.

Land condition decline and the main causes

Despite rainfall variability within the normal range over 15 years (2003–2018), land condition steadily declined at on-ground QGRAZE and rapid assessment sites in Queensland's Northern Gulf region. On-ground land condition discounts generally followed the pattern from the 2004 study of Shaw *et al.* (2007), with pasture composition and timber thickening being dominant. Soil surface condition and weed invasion discounts increased on high-value land types, compared with low-value types. Native timber thickening increased across most land types, and the rate of increase was similar for low- and high-value land types. Remote-sensing analysis of 28 years of data (1992–2020) found significant woody cover increase in every land type investigated, corroborating the on-ground monitoring. Since the original rapid assessments conducted in 2003/2004, retained carrying capacity declined from 72% of original capacity to 66% in 2015/2016. This suggests that, should

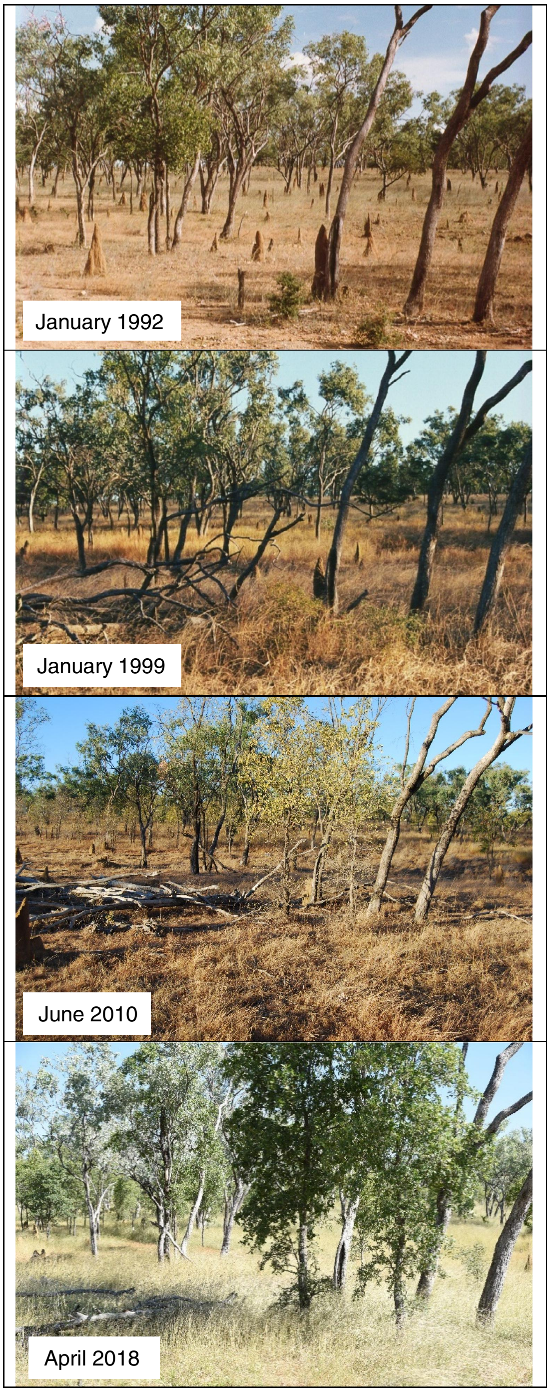

Fig. 12. A 26-year photo sequence graphically portraying the rate and effect of timber thickening occurring in the Northern Gulf region.

the current rate of land condition decline continue linearly, the grazing lands of the Northern Gulf will have lost 50% of their original carrying capacity by 2046. The fact that pasture composition and timber thickening are the dominant factors in the ongoing land condition decline implies that grazing pressure is above system capacity. Shaw *et al.* (2007) and Rolfe *et al.* (2016) assessed Northern Gulf cattle

Table 4. Linear trend analysis in mean spring PG values on 23 land types in the study region (1992–2020). *T* values and their significance (*P*) result from single sample *T* tests of the significance of Beta.

Land type	Beta	s.e.	*T*	*P*	Estimated increase (%)
NG06_Marine plains	0.46	0.08	5.48	< 0.001	12.8
NG03_Frontage	0.38	0.1	3.85	< 0.001	10.68
BD13_Loamy alluvials	0.38	0.06	6.71	< 0.001	10.66
NG13_Sandy forest	0.37	0.09	3.95	< 0.001	10.41
SG13_Sandy forest country	0.37	0.11	3.43	< 0.001	10.38
BD14_Narrow-leaved ironbark on deeper soils	0.35	0.05	7.47	< 0.001	9.8
NG11_Red earths	0.34	0.07	4.57	< 0.001	9.52
BD16_Ranges	0.33	0.06	5.67	< 0.001	9.1
BD11_Goldfields country – red soils	0.31	0.06	5.02	< 0.001	8.74
SG04_Frontage	0.31	0.1	2.98	< 0.001	8.71
NG07_Old alluvials	0.31	0.06	5.33	< 0.001	8.59
NG02_Coolibah country	0.3	0.06	4.82	< 0.001	8.31
BD15_Narrow-leaved ironbark on shallower soils	0.29	0.05	6.21	< 0.001	8.12
NG12_Sand ridge	0.28	0.07	3.8	< 0.001	7.84
NG14_Yellow earths	0.28	0.04	6.76	< 0.001	7.8
NG08_Range soil	0.28	0.04	6.57	< 0.001	7.76
NG04_Georgetown granites	0.25	0.05	5.39	< 0.001	7.06
BD20_Yellowjacket with other eucalypts	0.24	0.07	3.28	< 0.001	6.82
BD17_Red basalt	0.21	0.06	3.55	< 0.001	5.77
BD01_Black basalt	0.18	0.06	2.94	< 0.001	5.05
SG02_Bluegrass browntop plains	0.17	0.04	4.17	< 0.001	4.78
SG10_Mitchell grass	0.16	0.04	3.83	< 0.001	4.56
BD09_Downs	0.15	0.03	4.4	< 0.001	4.2

Beta values are scaled as percentage change per annum and estimated increase values in right most column assume linear change over 28 years. Alpha-numeric text (e.g. NG06) indicates the Grazing Land Management land-type code.

numbers as being greater than long-term carrying capacities. When in excess of sustainable stock numbers, cattle select and deplete the best pasture species (3Ps) and reduce pasture availability and fuel load for fire as a timber thickening control. In reality, producers in the region generally actively attempt to exclude fire so there is sufficient forage for their herd, further encouraging timber thickening.

Addressing timber thickening

Managing woodland thickening is problematic because of the following: (i) mechanical or chemical treatment to control thickening is not permitted by the Queensland Government, despite agencies agreeing that timber is thickening; (ii) control would mostly be unaffordable for grazing-only purposes, particularly on low grazing-value land types; (iii) tree competition and increased stocking pressure have reduced pasture yields to the extent that fuel loads are insufficient for effective burning to manage woodland density; (iv) in many areas, the growth of thickening species is significantly advanced and cannot be controlled by fire; and (v) in general, Northern Gulf graziers have actively excluded fire to maintain stock feed, so there are now two generations of land managers with little experience of using fire; and land managers are now also fearful of litigation if fire escapes, burning neighbouring properties. Therefore, reversing the thickening of native woody vegetation without reducing stocking rates, or using fire, machinery and chemicals, is unlikely.

Addressing excessive stocking rates

Irvine *et al.* (2025) reported on the change in cattle numbers throughout Australia from 1880 to 1980. Numbers in the Northern Gulf region increased substantially between 1940

Table 5. Linear trend analysis in mean spring PG values on 30 QGRAZE sites in the study region (1992–2020).

Site_Number	Beta	s.e.	T	P	Change (%)
1	0.57	0.2	2.92	< 0.01	16.03
2	0.54	0.07	7.48	< 0.001	15.26
3	0.54	0.12	4.66	< 0.001	15.11
4	0.53	0.13	4.21	< 0.001	14.77
5	0.5	0.09	5.87	< 0.001	14.02
6	0.49	0.13	3.73	< 0.001	13.72
7	0.43	0.13	3.2	< 0.01	12.02
8	0.42	0.11	3.95	< 0.001	11.83
9	0.41	0.1	4.21	< 0.001	11.39
10	0.38	0.09	4.28	< 0.001	10.54
11	0.35	0.08	4.31	< 0.001	9.74
12	0.35	0.12	2.96	< 0.01	9.67
13	0.34	0.09	3.65	< 0.01	9.52
14	0.31	0.2	1.58	n.s.	8.69
15	0.29	0.09	3.2	< 0.01	8.18
16	0.29	0.14	2.1	< 0.05	8.03
17	0.28	0.11	2.56	< 0.05	7.87
18	0.25	0.05	4.92	< 0.001	6.89
19	0.23	0.11	2.15	< 0.05	6.38
20	0.19	0.05	4.04	< 0.001	5.36
21	0.17	0.05	3.16	< 0.01	4.78
22	0.17	0.07	2.34	< 0.05	4.71
23	0.09	0.05	1.67	n.s.	
24	0.29	0.15	1.94	n.s.	
25	0.14	0.08	1.71	n.s.	
26	0.07	0.05	1.43	n.s.	
27	0.08	0.09	0.9	n.s.	
28	0.2	0.11	1.71	n.s.	
29	0.04	0.05	0.84	n.s.	
30	0.28	0.17	1.68	n.s.	

Beta values are scaled as percentage change per annum and estimate increase values assuming linear change over 28 years.

and 1980 (Fig. 3), an increase common throughout northern Australia's rangelands, in part owing to increased land subdivision (fencing), artificial water points, and dry-season urea supplementation. Moreover, cattle numbers are reputed to have been under-reported across the Northern Gulf, with the Australian cattle herd being suggested to be ~50% higher than reported in surveys, e.g. Meat and Livestock Australia (MLA) and national statistics e.g. ABARES (Fordyce *et al.* 2021). Although the majority of grazing businesses in the region operate on state leasehold land, successive governments have generally declined to enforce controls on stocking rates and land condition, except for the Great Barrier Reef catchment area. In 2008, the state government introduced the 'Delbessie Agreement' (State Rural Leasehold Land Strategy (SRLLS)), which provided practical policies and guidelines for the sustainable use, protection and rehabilitation of rural leasehold land in return for longer leases. A change of government meant that the SRLLS program concluded in 2014, and with it, any legislative linking of land condition to lease conditions. Although not forcing compliance, state and federal governments have provided significant and on-going investment in educational tools designed to assist beef producers in managing seasonal variability to improve both their financial situation and the resource condition (Rolfe *et al.* 2016). Various projects, involving business planning, herd productivity, grazing management, business analysis, mapping and resource monitoring tools have been in place for over 25 years. The recent transition to the Queensland Drought and Climate Adaptation and Farm Business Resilience Programs (https://www.longpaddock.qld.gov.au/dcap/) as well as the Australian Government's Future Drought Fund (https://www.finance.gov.au/government/australian-government-investment-funds/future-drought-fund) investment of ~A$5 billion to yield ~A$100 million annually for national drought preparedness projects, reinforces that livestock producers struggle to operate sustainable and viable businesses in a variable climate. The reported land condition decline in the Northern Gulf suggests that such government investment has been largely ineffective. However, management systems that can positively cope with the variable climate and be both financially and environmentally sustainable do exist.

A complex grazing enterprise

Managing large, family grazing enterprises in remote districts relying primarily on native pasture from highly variable summer-dominant rainfall requires coping with a high level of financial, production and natural resource management complexity. Breeder paddock numbers are constant or slowly built up despite seasonal conditions (Kernot *et al.* 2002), whereas the product, beef, requires a long lead time (3–5 years) from pregnancy to sale, with the majority being sold as a commodity into the export market, as live export or processed beef. Within these beef operations, the impact of stocking rate decisions or incremental land condition decline are often subtle and over long production cycles. As such, the link between resource condition and herd production efficiencies is not easily recognised by many producers or even agencies. Some producers adapt and thrive within these complex production environments. However, for others, financial pressures can dominate business decisions, such that when wet seasons are curtailed or fail, attention to land condition and stocking rates quickly becomes secondary. Whereas extensive beef businesses operate within an annualised cash flow and debt repayment environment, seasonal variability means pasture and herd productivity and income align poorly with annual business cycles and fiscal commitments. High stock numbers over a period of dry years affects cattle welfare, cattle mortalities, business position and land condition, with year-to-year fiscal commitments generally taking a much higher priority on family run properties than does land condition.

Evidence for improved land condition and profitability through moderate stocking rates

Systematic spelling of native pasture systems, together with management of stocking rates, are necessary to improve rangeland productivity and landscape function. Long-term grazing trial results suggest moderate stocking rates linked to 25% pasture utilisation produced by the 30th percentile rainfall amount are more profitable than are those commonly employed across enterprises in dry tropical northern Queensland (O'Reagain and Bushell 2011). McLean and Holmes (2015), in their summary of the 2013 Northern Beef Report, stated that in the northern beef industry 'business performance will be maximised when per animal performance is optimised, if the business is stocked at its long-term carrying capacity' (P14). The top 25% of northern Australian beef producers produce significantly more kilograms of beef per AE at virtually the same stocking rate as do average northern Australian beef producers. Per animal performance can be optimised economically only through good nutrition, and therefore good land condition. Isolated local examples of properties focused on land condition have demonstrated improved land condition, 3P pasture yields, weaning rates, and annual liveweight gain, along with lower mortalities, leading to increased total gross margins (Smith 2000; Rolfe 2012). Bowen *et al.* (2019), by using a 30-year herd modelling analysis based on weighted 2006–2018 prices, demonstrated that a set stocking scenario in the Northern Gulf with continuing steady 30-year land condition decline ended with a negative cumulative cashflow of (−A$2,212,900). A scenario modelled to steadily improve land condition through reduced stock numbers and wet season spelling improved the 30-year cumulative cashflow by A$388,300. Incorporating additional proven strategies (i.e. adequate phosphorus supplementation and pasture legume introduction) predicted a positive 30-year cumulative cashflow. Despite such evidence, widespread set stocking and overgrazing practices indicate most regional producers do not accept that 'fewer cattle are more profitable', and are confident their financial returns endorse their management practices. Additionally, there are no data suggesting that beef properties in poor land condition sell for less than similar beef operations with land in good condition, ruling out land condition as a sale incentive.

Despite large-scale government support for programs to improve resource condition over the past 30+ years, land condition decline across the Northern Gulf region of northern Queensland continues. The declining land condition and rangeland productivity reported here are possibly replicated in other extensively grazed regions of Queensland, even if ongoing trends have not yet been established. Consequently, a statewide land condition monitoring system, based on land types or broad vegetation groups, is required, so that trends can be established to inform producers, industry peak bodies and government.

We have demonstrated a low-cost hybrid monitoring methodology including historical data, rapid assessments and remote sensing. This methodology could be adopted elsewhere to build a picture of land condition change at the land system level, independent of management differences. Multiple stakeholders have an interest in landscape condition, and all need to recognise and accept the problem, and contribute to a solution. Except for ongoing development of satellite imagery and remote-sensing tools, government sponsored on-ground rangeland monitoring programs are unlikely to be developed, or revitalised, without the support of, and commitment from, the extensive grazing industry. However, such programs, whether at the state, regional or property level, will add limited value unless there is a concerted effort to analyse and use the results to inform both leasehold policy, and influence on-property grazing and stocking rate practices.

Conclusions

Remote-sensing analysis in combination with long-term on-ground QGRAZE and regional 'rapid assessment' data show a decline in Northern Gulf resource condition, landscape function and rangeland productivity. Land condition and productivity decline is evident across all major land types, although discounts for pasture composition, soil surface condition and weed invasion are most pronounced on the high-value grazing lands. Although low-value grazing lands are most affected by woodland thickening according to the on-ground data, remote sensing confirms timber thickening across all major land types.

If land condition decline continues, the region's original grazing potential could fall to 50% by 2046. The grazing landscape cannot sustain existing grazing pressures and set stocking practices. If current grazing pressure and grazing practices remain unchanged, this decline in the original grazing potential is likely to accelerate. Solutions first lie with the beef cattle industry, the community and government recognising that grazing management is negatively affecting productivity, native flora/fauna, water quality and the welfare of grazing stock, and second, in actually doing something about it. Tying community investment to resource management projects with measured resource condition outcomes would be a good start.

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