

Reef Rescue Research & Development

Technical Report

Improving grazing management practices to
enhance ground cover and reduce sediment loads
RRRD032



**Scott N Wilkinson, Gary Bastin, Chris J Stokes, Aaron A Hawdon,
Anne E Kinsey-Henderson, D Mike Nicholas, Vanessa Chewings,
Brett N Abbott, Karl McKellar and Joseph Kemei**

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Scott N Wilkinson¹, Gary Bastin², Chris J Stokes³, Aaron A Hawdon⁴, Anne E Kinsey-Henderson⁴, D Mike Nicholas³, Vanessa Chewings², Brett N Abbott³, Karl McKellar⁵, Joseph Kemei⁴

¹ CSIRO Land and Water, Canberra

² CSIRO Ecosystem Sciences, Alice Springs

³ CSIRO Ecosystem Sciences, Townsville

⁴ CSIRO Land and Water, Townsville

⁵ Queensland DAFF, Charters Towers



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Acronyms

CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DRCM	Dynamic Reference Cover Method (Bastin <i>et al.</i> , 2012)
DSEWPac	Department of Sustainability, Environment, Water, Population and Community
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GCI	Ground Cover Index, based on Landsat TM imagery (Scarth <i>et al.</i> , 2006)
ΔGC	Ground Cover deficit during drought due to grazing (Bastin <i>et al.</i> , 2012)
GLM	Grazing Land Management extension package
NRM	Natural Resource Management
QDAFF	Queensland Department of Agriculture, Fisheries and Forestry
RRRC	Reef and Rainforest Research Centre Limited
RRRD	Reef Rescue Research & Development

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Executive Summary

Context

Fine sediment, and attached nitrogen and phosphorus are impairing the ecological condition of the GBR. Three-quarters of fine sediment and large proportions of the total nitrogen and total phosphorus delivered to the GBR coast are derived from grazing lands, which occupy approximately 80% of GBR catchments. The principles of grazing management to minimise sediment loss are well known and extension packages are widely available. Intensive research at several sites has developed deep process understanding of the productivity and sediment loss outcomes of particular grazing practices. However, the practices which are appropriate for any given property across a region, and the effectiveness of those practices for improving water quality and enterprise profitability, are not well quantified or widely understood. This uncertainty can limit adoption of grazing practices which are sustainable in the long term. Spatial prioritisation is needed to determine where improved grazing land management is most needed and would be most effective.

It is recognised that historical grazing practices on individual properties have been influenced by a wide range of social and economic factors. This report investigates the long-term outcomes of a range of approaches to forage management, to help identify practice changes that can reduce the offsite impacts of the grazing industry and improve long term profitability.

Approach

This research used the Landsat-derived Ground Cover Index (GCI) of historical cover as a real-life, long-term experiment of the range of grazing practices which have been used on different properties in recent decades. A conceptual framework was developed which connects the environmental setting, grazing practices, forage productivity and utilization, vegetation cover and sediment lost to water courses. The links within this framework were quantified using GCI data, hillslope plot measurements and process modelling. A key feature of this research was to relate the process understanding from previous site-based research to ground cover remote sensing data. The purpose of this approach was to deliver a regional-scale, ground-truthed assessment of the potential for improved grazing practices to increase forage productivity and reduce erosion.

Focus properties were selected having high, medium and low levels of historical ground cover. The existence and robustness of relationships between cattle stocking rates and water quality outcomes was tested on focus properties by assessing land condition, infiltration and soil movement at representative sites, and modelling erosion rates. This approach was replicated across three defined soil type regions between Charters Towers and Clermont, being Chromosol (red goldfields soil), Sodosol (Duplex 'spewy' soils with sodic subsoils), and Vertosol (dark cracking clay soil). The assessments at focus properties were also related to those at sites where previous research has developed detailed process understanding (e.g., Bartley *et al.*, 2014)

Demonstrating productivity benefits from the grazing practices which can also reduce soil loss is important for achieving win-win outcomes in the context of a co-investment approach to facilitating grazing practice change in GBR catchments. Relationships between long-term stocking rates and forage productivity were tested by field measurement and grass production modelling. Broad scale assessments of the potential for practice change to improve pasture productivity were undertaken by modelling ground cover scenarios based on the focus properties.

The recently developed Dynamic Reference Cover Method was tested as a way to assess the relative differences in historical cover levels and grazing impact between properties across the soil type regions. This technique maps the deficit in historical grazed cover relative to nearby reference areas, isolating the effect of grazing from rainfall gradients. The robustness and limitations of cover deficit for property assessment across regions were established, and guidelines documented for ongoing application.

Key findings and applications

Long-term cover is broadly indicative of grazing land processes and function

This project has quantified how grazing land practices, processes and function can be related to cover remote sensing, including stocking rates, forage productivity, nitrogen availability, soil infiltration and soil stability. There was a large range in the long-term average of dry season ground cover between properties in each soil-type region, exceeding 20% over the 25 years of landsat-derived ground cover index data used in the project (1986–2010). During the three prolonged droughts in this period, the ranges in cover between properties exceeded 40%, due to lower coverage of perennial grasses including 3P species (perennial, productive and palatable) at low-cover properties. Contrasts in cover were evident between many adjacent properties, indicating that they were caused by contrasts in grazing practices.

Animal equivalent stocking rates were inversely correlated with historical cover levels, with low-cover properties having typically 2–4 times the stocking rates of high-cover properties. A High cover sites grew >2 times the forage biomass of low cover properties over the wetter than average 2011/12 wet season, and >3 times more over the drier 2012/13 wet season, in a grazing enclosure experiment. Standing dry matter within the paddocks (forage yield net of grazing) was up to 9 times higher at high cover sites. Medium cover properties had intermediate levels of forage production and standing biomass, between those on high and low-cover properties.

The resources required to grow forage (rain water and nutrients) were more efficiently retained on high cover sites than low cover sites, and this was consistent across soil types:

1. High cover properties had a much higher proportion of 3P grasses than the medium and low cover sites, irrespective of soil type. Land condition assessments were consistently higher and less variable on the high cover sites.
2. The soil infiltration capacity of high cover sites was measured to be 4 times that of low cover sites for both Chromosol and Sodosol soils, indicating that high cover sites could retain more water in the root zone of the soil profile for supporting forage production. Dominance of Indian Couch (*Bothriochloa pertusa*) in the pasture

biomass, which is associated with historical over-grazing during droughts, was correlated with impaired infiltration capacity.

3. The forage Nitrogen pool available to support plant growth and produce protein for livestock consumption was measured to be almost two times larger at the high-cover Chromosol site, relative to the low-cover site. During the 'growing season' a smaller Nitrogen pool would constrain forage production even when soil water is not limited.
4. Hillslope soil movement at high cover sites was measured to be 85% lower than at low cover sites, which assists retaining particulate nutrients and organic matter to support forage production.

Cover deficit isolates grazing impacts on ground cover across regions

The difference between property ground cover measured by GCI and local reference area cover in dry years (the grazing-induced cover deficit) was used to isolate the effect of recent grazing on property ground cover. This was more reliable than GCI itself, which displayed regional gradients that were correlated with rainfall gradients. There was a large range in cover deficit between properties within each region, highlighting the potential for targeting extension to properties with high potential for improving ground cover. We found that cover deficit performs most reliably when compared between properties having the same predominant soil type and pasture species.

Cover deficit can also be used to evaluate trajectories of property grazing impact, by benchmarking against other properties of comparable pasture composition, or of historical cover deficit. An acid test of the effectiveness of practice change will be how well ground cover is retained in the next drought, compared to previous droughts and other properties.

However, remotely-sensed ground cover and derived products form just one indicator of change. The effectiveness of practice change for improving productivity and reducing erosion should also be confirmed with on-ground assessments. We found Patchkey and Landscape Function Analysis to provide reliable indicators for assessing land condition.

Grazing management is about more than just cover

While forage productivity and hydrologic function are related to historical cover levels over decades, grazing management in the shorter term must consider more than just ground cover. For example, the widespread dominance of the exotic grass Indian couch in degrading pastures can give rise to high cover but low productivity and poor soil infiltration capacity.

Reducing stocking rates across the half of properties in each soil type having medium and low cover levels would initiate a recovery cycle. Increases in forage biomass and rebuilding of perennial species pasture with high basal area will, in turn, help to improve soil stability and rebuild the nitrogen pool, and to improve soil infiltration capacity to retain rainfall onsite to support plant growth, in a self-reinforcing cycle. The potential magnitude of these responses will increase with the degree of stock reduction. Recovery can be expected to continue for one to several decades depending on the degrees of initial degradation and stocking reduction, although thresholds of state-change may inhibit the recovery process.

The improvements in forage composition, soil and nutrient properties that are required for forage productivity to recover following run-down in dry periods have not been fully

accounted for in past grass production modelling, which may have over-estimated the recovery rate. We found that over-estimating the recovery rate leads to models over-estimating the safe stocking rates for sustaining land condition. If recovery occurs more slowly than previously assumed this also increases the value of conservative stocking during drought, because the long-term productivity losses associated with slow recovery will also be greater than previously assumed.

Maintaining high ground cover reduces erosion and increases productivity in the long term

There is a demonstrated capacity in the grazing industry to modify management practices when the benefits are widely understood. Many more graziers now recognise the importance of forage management, practice wet season spelling and vary stocking rates. This suggests that evidence-based reductions in stocking rates to provide productivity gains and reduce soil loss should be achievable.

Field measurement and modelling shows that forage production on properties with long-term high cover can be several times higher than that on long-term low cover properties. Beef production (kg/ha) also declines sharply above stocking rates which cause pasture composition to degrade. Stocking within the long-term carrying capacity should help maintain or improve forage production, recover perennial pastures, and increase soil water holding capacity and nitrogen availability to support animal protein production. Improving land condition in this way would reduce runoff volumes, and so reduce gully and streambank erosion rates also in the long term.

Property-scale modelling indicates that properties in the lower half of cover levels could be maintained at ground cover levels 10–20% higher during drought years than long-term hillslope soil losses would be 30–60% lower in the long term at paddock, property and regional scales. The magnitudes of erosion reduction were similar for properties with low and medium cover levels. Achieving these magnitudes of change will require reductions in stocking rates of approximately 50% for properties with low or declining historical cover, and somewhat smaller reductions for medium cover properties.

Supporting industry change

Across the grazing industry there is limited understanding of the linkages from forage utilisation to pasture composition, productivity and profitability. Quantitative approaches to forage budgeting and stocking rate decision-making are not yet commonplace. This research has provided quantitative data on the benefits of maintaining good land condition which has been of considerable interest to some graziers, and supports recent extension messages within the industry. Supporting practice change involves ongoing and focused extension activities with individual landholders, and the property cover deficit assessment developed by this project should assist in that process. Incorporating project findings into industry communication strategies, and simple but quantitative grazer tools such as photo standards for forage budgeting, should also assist practice change to improve the profile of grazing practices which both improve productivity and reduce sediment loss.

The priorities for public investment in grazing practice change to improve water quality at regional scale need to consider spatial variations in all erosion processes such as gully and streambank erosion, in addition to forage measures such as cover deficit. A framework for

integrating forage management into water quality improvement programs is proposed in Appendix 4.

Future directions

Extend the cover deficit assessment to all rangeland grazing properties in GBR catchments.

We have demonstrated the potential of cover deficit to monitor recent grazing impacts by removing rainfall gradient effects. Cover deficit should be used to assess the relative potential of each property in each catchment for forage management to be improved. It can also be used to evaluate the direction and magnitude of past and future property cover changes resulting from extension and water quality improvement programs such as Landcare, Stocktake and Reef Rescue. Cover deficit has the potential to improve assessments of grazing stress nationally.

Monitor the land condition responses to practice change

There have been many more studies of land degradation than recovery, yet the latter is our objective. Current understanding of land condition recovery rates is poor. Yet we have identified that sustainable stocking rates are sensitive to recovery rates, and recovery is expected to vary between landtypes. Reducing sediment loads to the GBR will require increases in ground cover. However, it will also require reducing the runoff that feeds the gully and streambank erosion dominating sediment loads in many areas. Sustainable change will require increases in forage productivity. Cover alone can mis-represent the changes to forage composition and hydrologic function that are required to improve productivity and reduce runoff.

We recommend that a long-term land condition field monitoring program be maintained to (i) evaluate the benefits of practice change, (ii) define rates of pasture recovery across different landtypes, (iii) enable more detailed interpretation of time series cover data, and (iv) inform stocking rate guidelines. The monitoring program should include pasture productivity, species composition, nutrient pool, soil infiltration capacity and water storage. The COSMOZ soil moisture probes (<http://www.ermt.csiro.au/html/cosmoz.html>) appear highly relevant to this purpose. Extensions to cover remote sensing should also be explored to map the degradation of pasture composition and establish baselines for recovery. Combining land condition field surveys with cover deficit has potential to better define land condition mapping across climate zones than using ground cover directly.

Map the cost-effectiveness of practice change investment

There is an increasing need for a more detailed technical basis for investment priorities in terms of the relative cost-effectiveness of different practice changes, including forage management and remediation of erosion features. The cost-effectiveness of investment will also be improved by considering spatial patterns in environmental drivers of all erosion processes, such as soil type, terrain and climate. Broader adoption of improved forage management would be assisted by further case studies of productivity and economic outcomes.

1 Introduction

1.1 Context

The current loads of fine sediment, and attached nitrogen and phosphorus have been identified as impairing the ecological condition of the GBR, including reducing coral diversity and increasing macroalgae cover (De'ath and Fabricius, 2010), and reducing seagrass cover. Large nitrogen loads trigger Crown of Thorns Starfish outbreaks which alone are responsible for reducing GBR coral cover by 42% since 1985 (De'ath *et al.*, 2012).

Grazing lands occupy approximately 80% of GBR catchments and contribute approximately 75% of fine sediment to the GBR coast (Brodie *et al.*, 2003; Thorburn and Wilkinson, in press). More than 60% of total Nitrogen and total Phosphorus is delivered to the GBR coast attached to fine sediment (Kroon *et al.*, 2012). The basic principles of grazing management in Queensland rangelands are well developed, although in the past the focus may have been aligned more to production than to water quality management. Several extension and education programs/packages are available to put these principles in the hands of graziers (e.g. Grazing Land Management, GLM; Mclvor 2012). However, the effectiveness of particular practices for improving water quality and enterprise profitability are not well quantified, which can limit adoption. Spatial prioritisation is needed to determine where management will be most needed and most effective. This report addresses these needs for quantitative information.

The interactions between the local environmental setting, grazing practices, vegetation cover and annual sediment lost to water courses can be illustrated in a conceptual framework (

Figure 1). The upper chain of linkages in this framework describes how the potential for hillslope erosion in each wet season is strongly dependent on the vegetation cover at the end of the preceding dry season. Vegetation cover is related to forage biomass, and stocking rate (animals per ha) is the main grazing practice impacting the proportion of pasture biomass removed by grazing during each year (termed the pasture 'utilisation rate'). Given the highly variable rainfall experienced in GBR catchments (Petheram *et al.*, 2008), the pasture productivity and available biomass vary greatly between years. Therefore, adjustment of stocking rates can be important to prevent excessive pasture utilisation in dry years. To sustain current land condition requires utilisation rates in the range 10–30%, particularly in years of less than median rainfall (Mclvor, 2010; Thorburn and Wilkinson, 2012).

At a given site in the short term, the effect of a given stocking rate on vegetation cover and erosion depends on the local land condition, which can be simplistically defined as the capacity to produce useful forage biomass (Mclvor *et al.*, 1995). In the long term, grazing practices continue to modify land condition. For example, excessive pasture utilisation results in land degradation (McKeon *et al.*, 1990). Land degradation results in change in community composition of pasture (McKeon *et al.*, 2004; Ash *et al.*, 1997), and accelerated runoff and erosion (Mclvor *et al.*, 1995; Bartley *et al.*, 2010a; Silburn *et al.*, 2011). This longer-term feedback is shown in blue in

Figure 1.

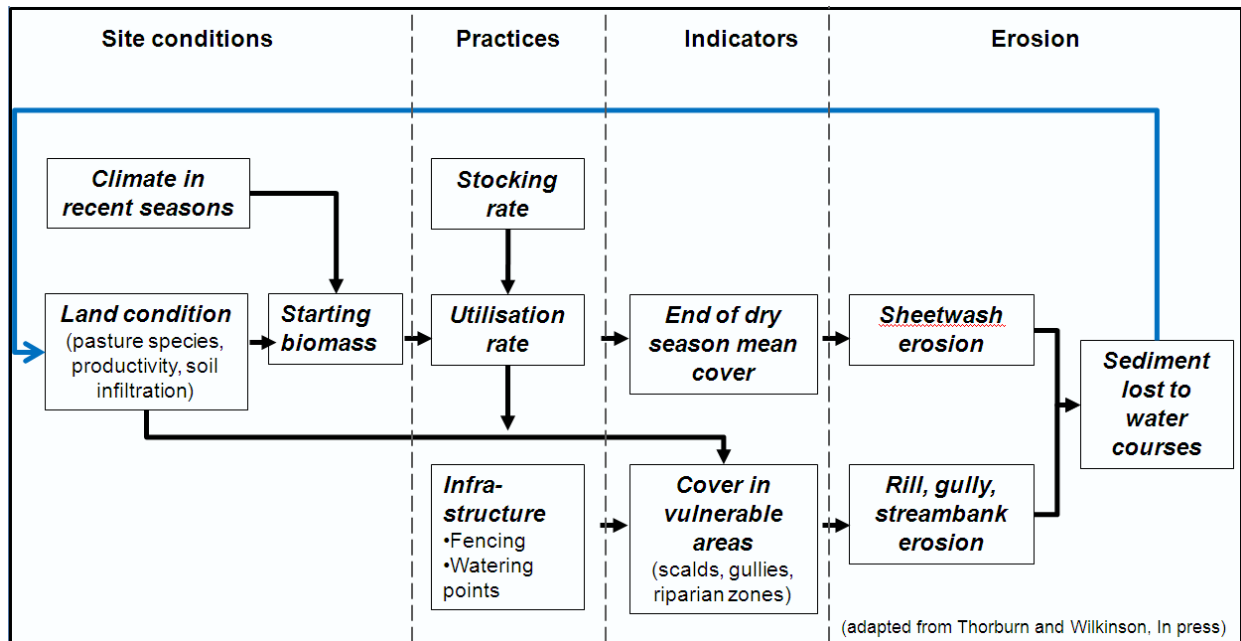


Figure 1. Conceptual framework of the impact of grazing practices on sediment loss (adapted from Wilkinson and Thorburn, 2013).

Hillslope ground cover management also impacts the runoff volumes which drive rill, gully and streambank erosion (Bridge *et al.*, 1983; Owens *et al.*, 2003). Soils are especially vulnerable to vegetation damage in proximity to drainage lines (Trimble and Mendel, 1995). More than 90% of sediment lost from hillslopes to streams can be derived from <10% of the catchment area (Bartley *et al.*, 2010b), and areas of hillslope rilling and scalding, gully and streambank erosion can deliver more than three quarters of total catchment fine sediment yield (Wilkinson *et al.*, 2012). ‘Best-practice’ grazing thus controls the spatial (as well as temporal) distribution of grazing pressure using infrastructure (fencing, water points).

Due to the spatial and temporal variability in grazing systems and erosion processes, achieving accurate relationships between stocking rates and soil loss requires long-term and intensive monitoring-based research at plot, hillslope and catchment scales. Two examples in the Burdekin catchment are at Virginia Park Station near Mingela (Bartley *et al.*, 2010a; Bartley *et al.*, 2010b; Bartley *et al.*, 2014), and a comparative trial of 5 grazing treatments at Wambiana west of Charters Towers (O'Reagain *et al.*, 2011; Orr and O'Reagain, 2011). Such monitoring has found that reducing stocking rates increases ground cover at property scale, improves pasture composition to include more perennial biomass, may reduce runoff volumes depending on the degree of land degradation, and reduces rates of hillslope sediment loss under comparable climatic conditions. It has also been demonstrated that moderate stocking within the long-term carrying capacity is more profitable than heavy stocking at ~2 times the LTCC (O'Reagain *et al.*, 2011). Case studies elsewhere are consistent with this also (Landsberg *et al.*, 1998).

However, it is clear from driving around grazing regions that there is a wide range of management practices occurring between properties. While climatic drivers show regional-

scale trends, each property is operated independently of its near neighbours. As valuable as the quantitative and robust findings from long-term intensive research are, that research is constrained to focusing on a limited number of sites and grazing practices. Regional scale assessments of the potential to improve grazing practices, and the impacts on pasture productivity and soil loss, are difficult to extrapolate directly from case study sites to all properties in a region. Such assessments remain a key knowledge gap for understanding the potential to improve grazing practices, and for quantifying the impact of practice improvement on productivity and soil loss outcomes. This report develops, trials and validates techniques for undertaking such regional assessments, to better support future decision making at property scale.

For several years the Landsat-derived ground cover index (GCI) has provided spatial images of dry-season ground cover to graziers and extension officers via the VegMachine software, to inform property management planning for individual properties. More recently, a remote-sensing technique has been developed which removes the effect of spatial variations in climate (rainfall) on ground cover, to isolate the impact of grazing practices. This is called the cover deficit technique (Bastin *et al.*, 2012), which calculates the difference in ground cover in a particular season spatially, relative to local high-cover reference areas. Both GCI and cover deficit work best during drought periods when cover is most affected by grazing. However, to date the cover deficit technique has not yet been widely tested beyond research sites, and neither approach has been widely applied to entire regions, or populations of properties. Such analysis techniques present promise for undertaking regional assessments of property grazing practices and their implications for downstream water quality.

This report couples remote sensing analysis with ground-truthing of cover estimates, and rapid field measurements of pasture productivity and hydrologic processes, to investigate the relative costs and benefits of a range of property stocking rates. The research also uses the remote sensing analysis to investigate the extent of practices at regional scale.

1.2 Project Objectives

At the commencement of the project the objectives were to:

- 1) Develop relationships for key land types between grazing practices, land cover and condition, and erosion rates.
- 2) Estimate the landscape-scale impacts on erosion of future changes to grazing practices.
- 3) Estimate the likely outcomes of changing grazing practices in terms of pasture productivity and beef production.
- 4) Build industry capacity to interpret cover products and management tools for indicating productivity and erosion resulting from grazing practices, and for identifying priorities for practice change.

The remainder of this report is divided into sections describing the research activities that address the above objectives as follows:

- Firstly the study region and research approach to selecting focus properties that represent the observed variations in vegetation cover are described in Section 2.

- Section 3 describes site measurements of processes and function (land condition) resulting from historical grazing practices on focus properties, to determine how practices have impacted land condition, and what would be required to improve ground cover, land condition and pasture productivity and soil stability (Objectives 1, 4).
- In Section 4 remote-sensing data is used to assess the historical grazing impacts on all properties across the regions, based on the spatial and temporal dynamics in historical ground cover and the recently-developed dynamic reference cover method (Objective 1).
- The reduction in erosion which would result from achieving defined regional cover scenarios (and their accompanying practices) is then assessed using modelling, validated to field data (Section 5)
- The improvement in pasture productivity resulting from cover scenarios, and the change in land condition required, is assessed using modelling and field data in Section 6 (Objectives 2, 3).
- Findings of the above sections are synthesised and set in the context of previous research in Section 7.
- Overall conclusions are made in Section 8.

2 Study area and research approach

2.1 Soil type and rainfall regions

The project investigated the links between property grazing practices (stocking rates), vegetation ground cover, land condition and soil erosion within 3 regions between Charters Towers and Clermont. Each region focused on properties with a predominant soil type, since stocking rates can vary between land types and ground cover remote sensing can be sensitive to the soil colour. The regions contained properties with a range of ground cover levels, but consistent mean rainfall (within 100 mm/yr), so that potential pasture productivity was reasonable consistent across each region (Figure 2a).

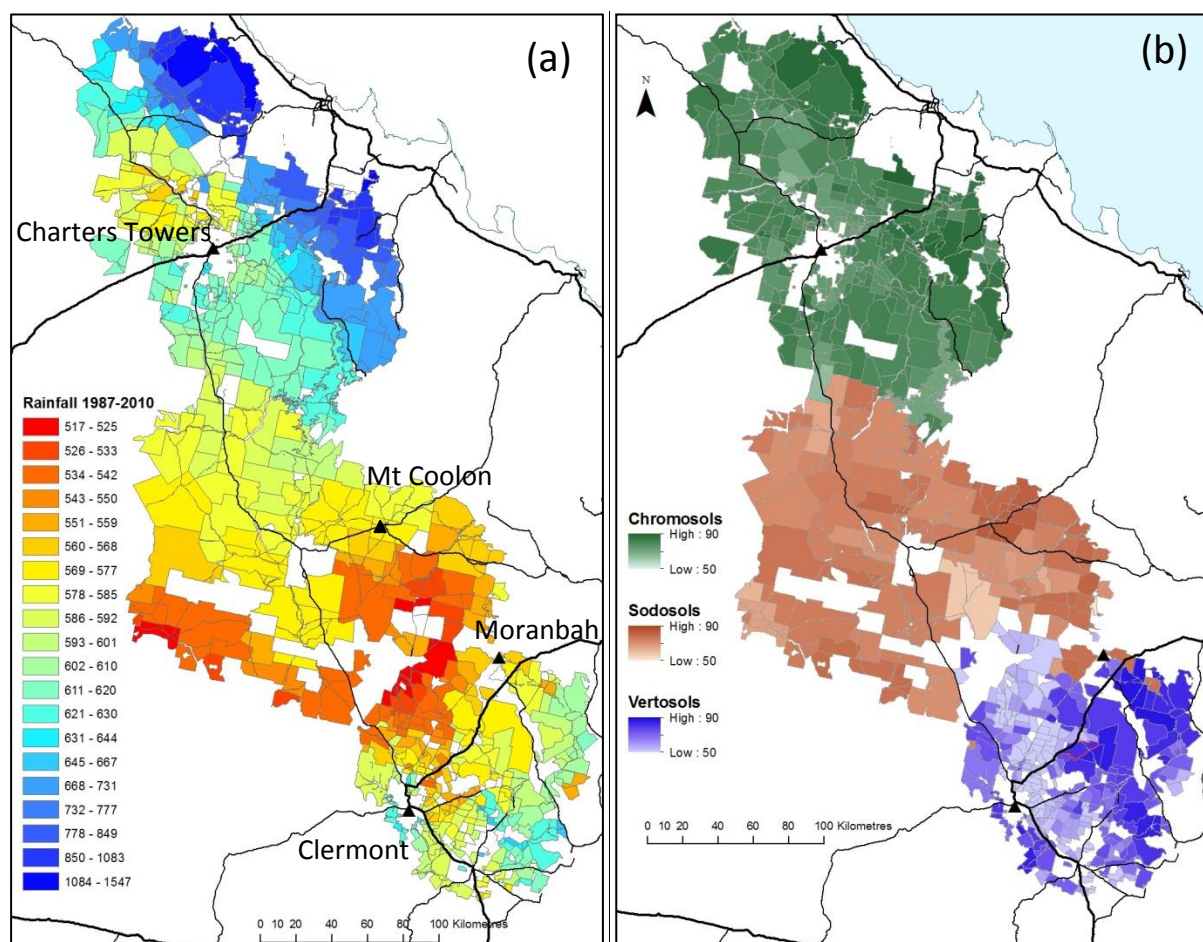


Figure 2: Property averages of (a) Mean-annual rainfall and (b) mean-annual dry-season ground cover (1987–2010) across the 3 soil type regions. The black lines are main roads and grey outlines are property boundaries.

The three regions were Chromosol (red goldfields soil) within ~50 km from the township of Mingela, east of Charters Towers, Sodosol (Duplex ‘spewy’ soils with dispersive sodic subsoils) within ~80 km of Mt Coolon, and Vertosol (dark cracking clay soil) within ~100 km of Moranbah. These soil types occur extensively in the Burdekin and Fitzroy basins. A range of mean annual ground cover was evident across each region, including between adjacent properties, indicating that stocking rates was an important determinant of ground cover (Figure 2b). There were 75 properties of area >10 km² in the defined Chromosol region, 70 properties in the Sodosol region and 118 properties in the Vertosol region.

2.2 Focus properties of high, medium and low cover

Three focus properties were selected in each region, having high, medium and low levels of ground cover). The selection process involved:

1. Properties in each region were categorized into three groups having high, medium and low property cover, based on the mean-annual value of GCI
2. Candidate properties were identified based on likely willingness to be involved
3. Some candidate properties were excluded because they were outliers in terms of rainfall, slope or excessive tree cover.
4. Candidate properties were contacted by letter and telephone.
5. A short-list of properties was visited, and:
 - a. Graziers were interviewed about property management practices, and to define paddock boundaries.
 - b. A paddock was selected for which historical stocking rates were quantified and land condition was assessed.

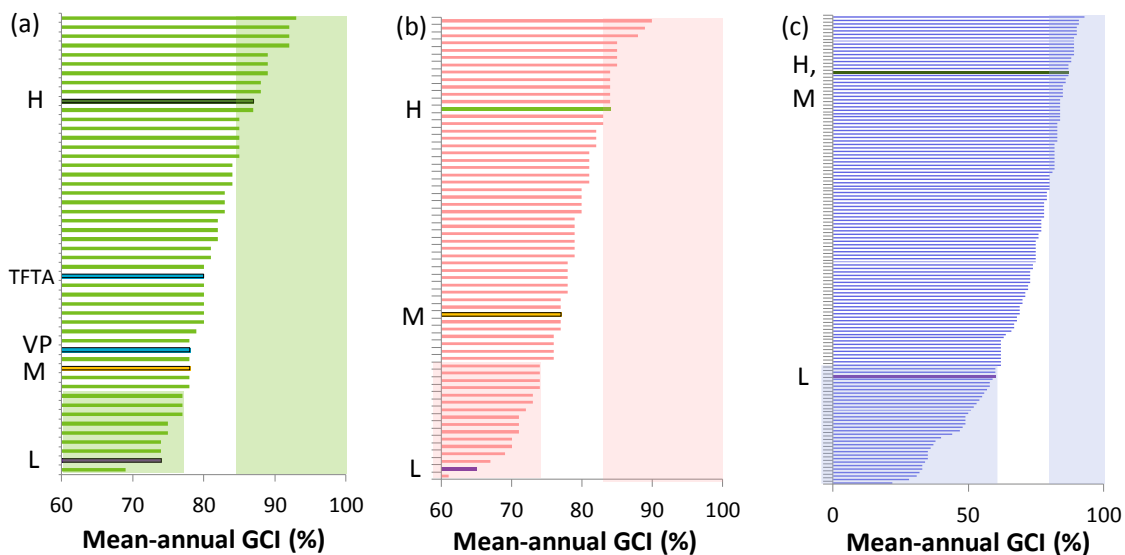


Figure 3: Property rankings of mean-annual ground cover index 1987–2010 for the (a) Chromosol, (b) Sodosol and (c) Vertosol regions. The cover ranges of low and high cover categories are indicated by shading, and the high, medium and low focus properties are labelled (H, M, L, respectively). The rankings for Virginia Park (VP) and Townsville Field Training Area (TFTA) relate principally to the practices prior to adoption of reduced forage utilization and wet season spelling at Virginia Park (Bartley *et al.*, 2010a), and cessation of grazing leases at TFTA.

Three focus properties were selected in each of the chromosol and sodosol regions. In the vertosol region two properties were selected, one having two separate paddocks representing high and medium cover. To maintain the anonymity of the focus properties their attributes as presented in this report may be adjusted slightly from their real values (Table 1). To help relate the grazing practices on focus properties to water quality outcomes, and to indicate the rates of response to improved grazing management, a further two properties were included in the Chromosol region, where monitoring records of grazing practices, land condition and runoff water quality were available.

Table 1. Characteristics of the focus properties selected for the project.

SOIL TYPE	COVER LEVEL	AREA (KM ²)	MEAN SLOPE (%)	MEAN RAINFALL (MM/YR)
Chromosol	High	100	4.5	680
	Medium	150	3.0	620
	Low	40	2.8	670
	Virginia Park	160	2.3	660
	TFTA ^a	140	2.4	650
Sodosol	High	129	1.8	580
	Medium	250	3.8	580
	Low	40	1.0	540
Vertosol	High / medium	110	NA	580
	Low	25	NA	590

^a In this report TFTA denotes the southwest portion of the Townsville Field Training Area, which is the former Dotswood cattle grazing property now managed for military training. Within this, high, medium and low cover areas are defined based on different sectors which had different levels of grazing pressure prior to 2001, after which grazing was excluded.

3 Site cover, condition and hydrologic function

3.1 Methods

3.1.1 Grazing practices

Properties that were selected to be part of this study were visited individually by the members of the study team. At “kitchen table” meetings aspects of historical property management were discussed in an attempt to (i) understand the grazing practices and property management styles that led to the differing properties having differing ground cover, and (ii) to select a paddock on the property in which the land condition impacts (pasture production and environmental impacts) of the stocking rates and any ancillary aspects of grazing land management could be assessed. Land holders were asked a range of questions in an informally structured format and responses were transcribed after the interview. Questions asked included:

1. What do you base your stocking rate on (personal observations, actual grass yield, historical, age/size of cattle, etc).
2. Principal cattle type on the paddock eg fatteners, breeders etc. Is this a constant stocking strategy on this paddock?
3. Do you stock the paddock all year or do you cease/reduce grazing if cover/grass biomass becomes problematic?
4. Do you wet season spell or include spelling in a rotation.
5. Has there been a history of spelling or is spelling a new process for this paddock?
6. Is the stocking rate and management practices similar on the target paddock to the rest of the property?
7. Has there been a history of subdivision of the paddock?
8. Does the paddock get burnt due to management? If yes, frequency and time of year?
9. Have there been wild fires through the paddock? If yes, frequency and time of year?
10. Is there a history of tree clearing in the paddock? If yes when and what extent?
11. Has there been pasture improvement in the paddock? If yes when and what extent, species/fertilizer regimes, etc?
12. Have you noticed a change in grass cover and species composition over the years? Can you explain why? (ie are there theories that we/science are unaware of?).
13. Can you give an indication as to the timeline for cover and species change?
14. How long did it take before you thought this was affecting animal performance & profitability (for both positive and negative changes)?

Participants were asked to provide records or estimates of cattle numbers, age and sex. The stocking rates were converted to animal equivalent (AE/km²) based on the ratios of Cow=1 AE, calf=0.66 AE, bull=1.45 AE and dividing by the paddock area.

3.1.2 Land condition assessment

Within each focus property, land condition was assessed over a 100m hillslope transect, using two measurement methods; Patchkey and Landscape Function Analysis. These transects were also used for monitoring soil erosion and measuring the infiltration capacity of the soil surface.

3.1.2.1 Patchkey

Patchkey (Abbott and Corfield, 2006) is a technique for rapid assessment of land function at a finer resolution than the QDAFF ABCD rapid assessment, but broader than Land Function Analysis (LFA; see below). Patchkey classifies land into alpha numeric descriptors ranging from A1 (best condition) to D11 (worst condition) using a 2 metre “patch” as the minimum observed area. In this study the proportion and number of patch types was determined along each 100 metre transect. The Patchkey assessment was undertaken by a trained operator recoding data on a prewritten software package designed specifically to collect patchkey information. The metrics collected allow for the analysis of Patchkey proportion of land type (A,B,C,D), the patch length, dominant functional group, plant basal area, litter levels, erosion levels and biomass at patch scales. Table 2 describes the relationships generated through the Patchkey package.

3.1.2.2 Landscape Function Analysis

Landscape Function Analysis (LFA) is a monitoring procedure that uses field observations to assess rangeland function (Tongway and Hindley, 2004). The field methodology uses visual indicators that are related to physical, chemical and biological processes at the vegetation patch and hillslope scale. Consequently the assessment can be correlated with measures of physical function such as infiltration and erosion. The method also provides spatial relationships between patches that form a landscape. Surveys of the same area through time provides and insight into the dynamics and trajectories relating to functional criteria.

The frequency and spatial characteristics of all patches along each transect were measured down to approximately 2 cm. The initial LFA survey did not use any preconceived patch names or types, although subsequent surveys referred to previous nomenclature. The biophysical condition of a subset of patches, representative of those present on each transect, were then scored to develop a set of Soil Surface Condition (SSC) indices relating to Soil Stability, Infiltration and Nutrient Cycling. These were used to characterise the condition of each transect through time and for comparisons between transects at a point in time.

3.1.3 Forage biomass

Standing forage biomass was estimated across the 100 m transects based on visual estimates of standing biomass for each patchkey patch type. The visual estimates were calibrated for each soil type by clipping all forage from ~10 quadrates each of 1 m² covering a range of yield estimates, and drying and weighing in the laboratory, then fitting a regression between the biomass estimates and measured weights.

Table 2. Relationships between components of the Patchkey assessment, with corresponding condition assessment.

STRUCTURAL CLASSIFIERS ^A				FUNCTIONAL CLASSIFIERS ^B		PATCH ID ^C	ABCD CLASS
GROWTH FORM	FUNCTIONAL GROUP	PG BASAL AREA	COVER (BARE GROUND)	LITTER COVER	EROSION / DEPOSITION		
Tussock	3P	H	H (I)	M-H	I / I	A1	A
Tussock	3P	H	H (I)	L-M	I / I	A2	A
Tussock	3P+IPG	M	H (I)	M-H	I / I	B1	B
Tussock	3P+IPG	M	M (L)	L-M	L / I	B2	B
Tussock	3P+IPG	L	H (I)	H	L / L	C1	C
Tussock	3P+IPG	L	M (L)	M	M / L	C2	C
Tussock	3P+IPG	L	L (M)	I-L	H / L	C3	C
Stolon	EXPG	H	H (I)	M-H	I / L	B3	B
Stolon	EXPG	H	H (I)	M	I / L	B4	B
Stolon	EXPG	M	M (L)	L	L / I	B5	B
Stolon	EXPG	M	M (L)	I	L / L	B6	B
Stolon	EXPG	L	H (I)	H	M / M	C4	C
Stolon	EXPG	L	M (L)	M	M / L	C5	C
Stolon	EXPG	L	L (M)	I-L	H / L	C6	C
Mixed	IPG+ANN	L	M (L)	M	M / L	C7	C
Mixed	IPG+ANN	L	L (M)	L	M / L	C8	C
Annual	ANNS	I	H (I)	H	M / M	C9	C
Annual	ANNS	I	M (L)	M	M / M	C10	C
Annual	ANNS	I	L (M)	I-L	H / M	C11	C
Annual	ANNS	I	H (I)	M-H	M / M	D1	D
Annual	ANNS	I	M (L)	L	H / M	D2	D
Annual	ANNS	I	L (M)	I	H / L	D3	D
None	NOSPEC	N	H (I)	M-H	M / M	D4	D
None	NOSPEC	N	M (L)	M	H / M	D5	D
None	NOSPEC	N	L (M)	I	H / H	D6	D
None	NOSPEC	N	I (H)	I	H / I	D7	D
Shrub	3P /IPG	M	H (I)	H	I / M	D8	D
Shrub	3P/ IPG	L-M	M (L)	L-M	L / M	D9	D
Shrub	NOSPEC	I-L	H (I)	H	L / L	D10	D
Shrub	NOSPEC	I-L	M (L)	L-M	L / L	D11	D

^A 3P = palatable, perennial and productive grasses (including decreaser native perennial tussock grasses and exotic perennial tussock grasses; IPG = increaser perennial tussock grasses; EXPG = exotic perennial grasses (at present specifically stoloniferous EXPGS); ANNS = annual grasses and forbs, (including native legumes); ANN+IPG = annuals plus some increaser perennial grasses; NOSPEC = no pasture species present; as well as some combinations of these e.g. IPG+3P; ANNS+3P/IPG.

^B H=high, M=medium/moderate, L=low, I=insignificant

^C PATCH ID = individual patch class identifier; Patch Functional Group = IDs for each functional group x PG basal area grouping; ABCD class = broad grouping according to ABCD classification.

3.1.4 Infiltration

High values of soil surface infiltration capacity generally indicate lower runoff at hillslope scale, although there can be considerable scatter in the relationship due to the effects of spatial heterogeneity across hillslopes (Roth, 2004). Infiltration capacity measurements which involve ponding water on the surface can be used to represent the soil runoff generation capacity under heavy rainfall.

Measurements of infiltration capacity were completed using single ring infiltrometers (Eldridge, 2003) which use the rate of fall of a ponded water source to estimate infiltration. A steel ring was driven into the ground, and the edges were sealed with wax to mitigate effects of surface disturbance. The ring was filled with water and a float used to determine the change in water level against a gradational measure through time. Prior to each measurement, a Soil Surface Condition assessment was made of the area inside the ring. One bulk density sample (0–5 cm depth) was also collected from each ring.

Nine infiltration measurements were made close to each of the LFA transects, more than the four sometimes recommended as sufficient to estimate site infiltration rates (Eldridge, 2003). To represent the effect of variability at each site three measurements were each made on low, medium and high-cover patches as defined from the LFA survey. No measurements were taken under tree canopies where infiltration capacity can be expected to be elevated. The soil profile was described in at one location on each transect.

Within the Chromosol soil region, infiltration was measured at three additional sites as well as on the focus properties. Six infiltration rings were used to characterise the ‘typical’ condition of hillslopes at Virginia Park. Three infiltration rings were measured inside a cattle enclosure on Meadowvale Station, that has had practically no grazing for more than 10 years (Hawdon *et al.*, 2008). On the TFTA, 12 rings were used to characterise soil infiltration in a catchment that has had no grazing for more than 10 years but is used for military training exercises. Infiltration measurements were not undertaken for the Vertosol soils due to high frequency of macropores in this soil type.

3.1.5 Soil movement

Soil movement was measured using five arrays of erosion pins installed at 20m intervals along each LFA transect. Each array comprised four pins, arranged at the vertices of a one metre square. Digital callipers with sub-millimetre precision were used to measure the distance between the top of each erosion pin and a metal washer sitting on the ground surface from which litter had been removed. Comparison of individual pin measurements between dates indicated whether erosion (measurement increase) or deposition (measurement decrease) had occurred. The total cover of vegetation and litter was assessed over the 1m² area at the time of each measurement. Soil movement was not monitored on the Vertosol soil type, which undergoes large surface movement during wetting and drying cycles.

3.2 Results

3.2.1 Grazing practices

The historical stocking rates provided by the producers (animals per unit area) were highest on low cover properties and lowest on high cover properties, across all soil types. In other words, where ground cover from satellite imagery was high available grazing land for each animal was also high and conversely where ground cover was low available land area for each animal was low (Figure 4). On average, high cover focus properties had stocking rates about half those on medium cover properties, which in turn had stocking rates about half those on low-cover properties. Of the additional Chromosol properties included in the study, the TFTA has had negligible grazing pressure since 2001, when grazing leases ceased. Virginia Park had stocking rates similar to the medium cover property until 2002, when they were reduced to levels similar to the high-cover property.

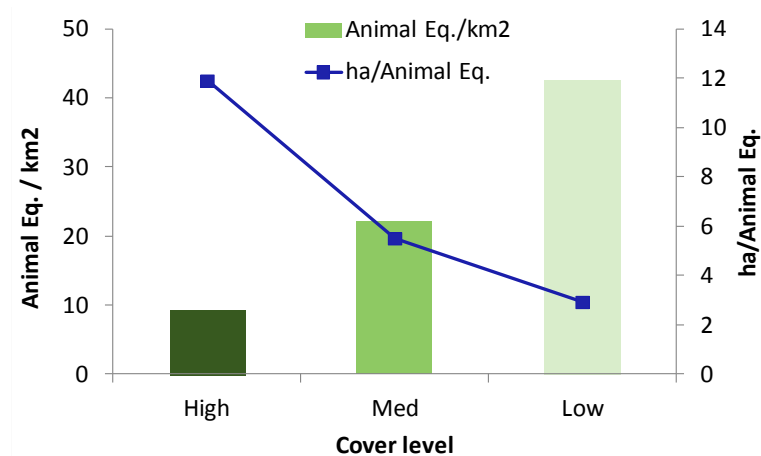


Figure 4. Stocking rates as animal equivalents for focus properties in each cover level, averaged across the three soil types.

All of the focus properties paddocks assessed had continual stocking with breeder herds over the period of records (Table 3). Fire was not used as a management tool in any of the paddocks, and wildfire had been rare or absent. Tree clearing had occurred on the vertosol high cover property and selective use of tree poison was reported at several properties.

Table 3. Stocking rates and grazing land management of the study paddocks on each focus property.

SOIL	CHROMOSOL			SODOSOL			VERTOSOL		
Cover	High	Med	Low	High	Med	Low	High	Med	Low
Record period	'86-	'86-	'86-	'00-	'05-	'90-	'07- ^A	'99-	'86-
Grazing timing	Cont. ^B	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.	Cont.
Herd type	B ^C	B	B	B	B	B	B	B	B
Average Stocking rate (AE/km ²)	9	28	35	13	11	22	6	28	71
Fire frequency (years) ^D				5			5		
Tree clearing (year) ^D							2000		
Improved pasture (area%) ^D				20					
Pasture composition change ^{D E}				NP+ BP+					
Paddock subdivision ^D				2001					

^A Negligible stocking prior to 2007^B Continuous^C Breeder^D Crossed cells indicate that this had not occurred. Where tree clearing occurred, original tree cover was fairly open.^E NP is native perennials, BP is *Bothriochloa pertusa* (Indian Couch).

3.2.2 Forage Biomass

As a consequence of historical grazing practices, high-cover sites had visibly more pasture biomass than low-cover sites (Figure 5). This was borne out by the biomass surveys, which revealed that high and medium cover sites had standing forage biomass generally >2000kg/ha, with <10% of those sites being below that level (Figure 6). These levels can be regarded as the upper end of the historical range due to above-average rainfall in preceding wet seasons. Grazing impact on pasture was much more apparent in 2013 than in earlier, wetter years.

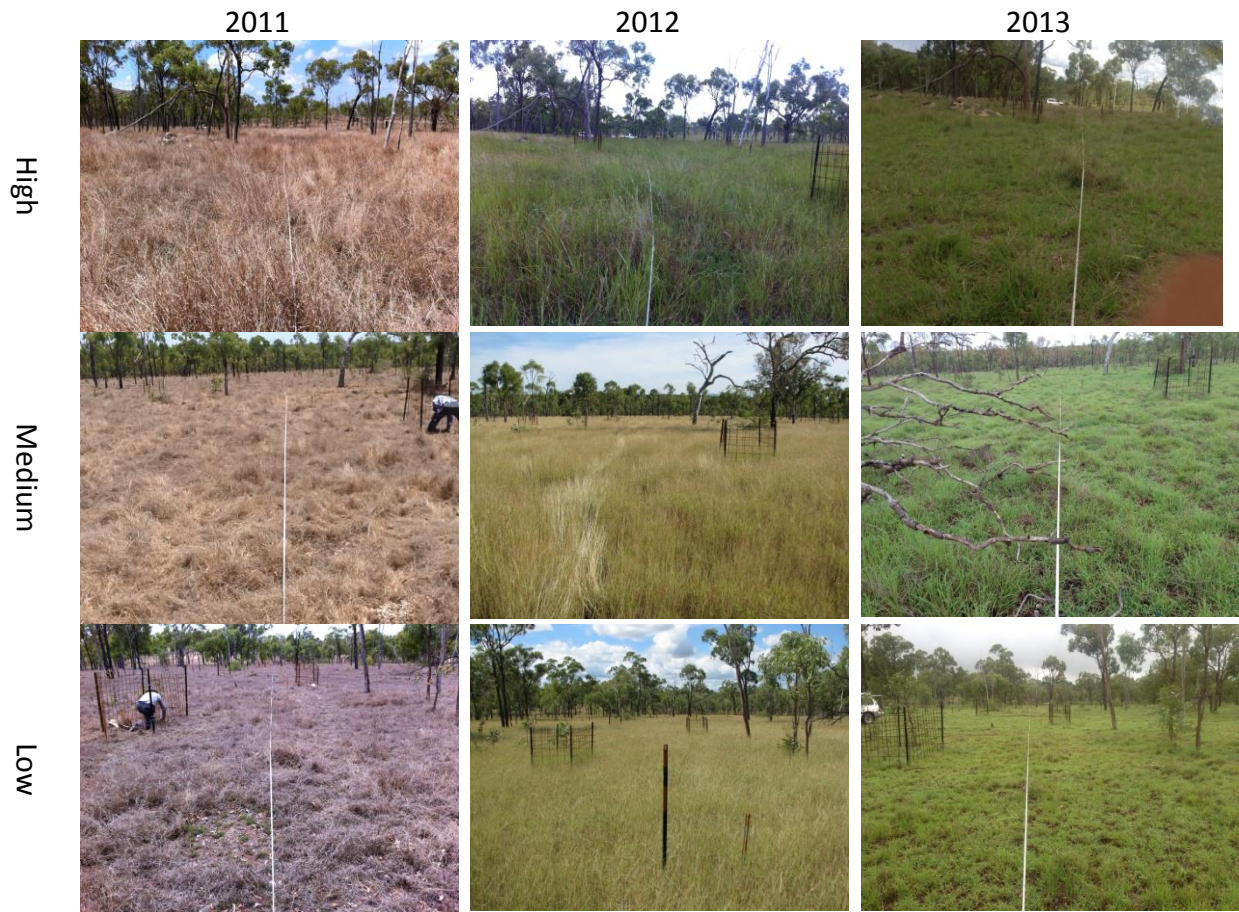


Figure 5. Images of Chromosol high, medium and low cover transects for each year of monitoring.

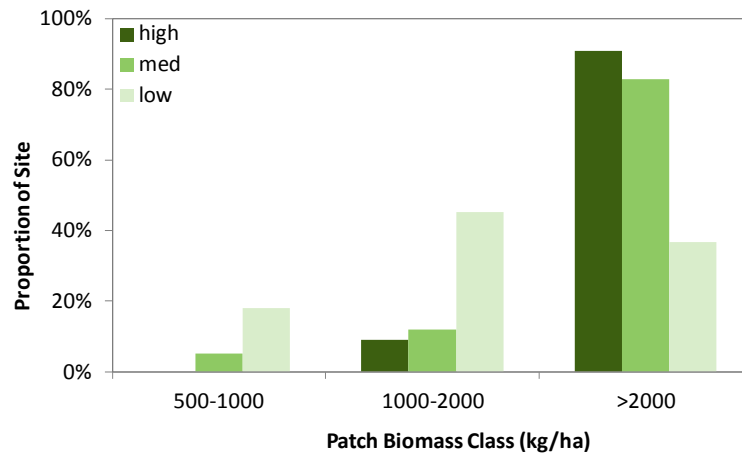


Figure 6. Forage standing biomass (kg/ha) by cover class, averaged across soil types and wet-seasons.

3.2.3 Patchkey assessment of land condition

Patchkey surveys indicated that land condition was generally better at sites with higher cover levels (in terms of mean-annual GCI). High cover properties had a higher proportion of land in A and B patch type while low cover properties had a higher frequency of C and D patch types (Figure 7).

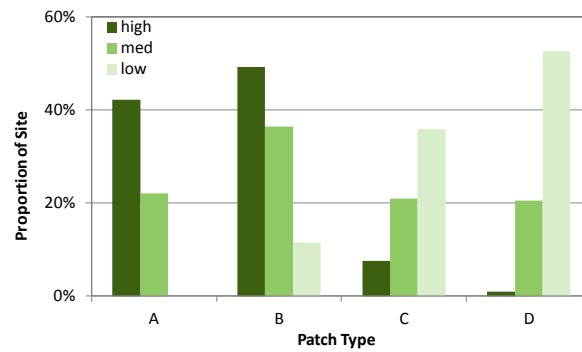


Figure 7. Proportions of patch type across all soil types and cover levels

Perennial grasses, with higher basal area, were much more dominant on high and medium cover properties (Figure 8). These grasses are better able to remain productive in dry periods and in response to cattle grazing. High cover sites also had a larger number of 3P species present (2–4 depending on soil type) than low-cover sites (0–2 depending on soil type). Signature 3P species such as *Themeda triandra* (Kangaroo grass) were absent from all low cover sites, and also from the medium cover site in Chromosol soils.

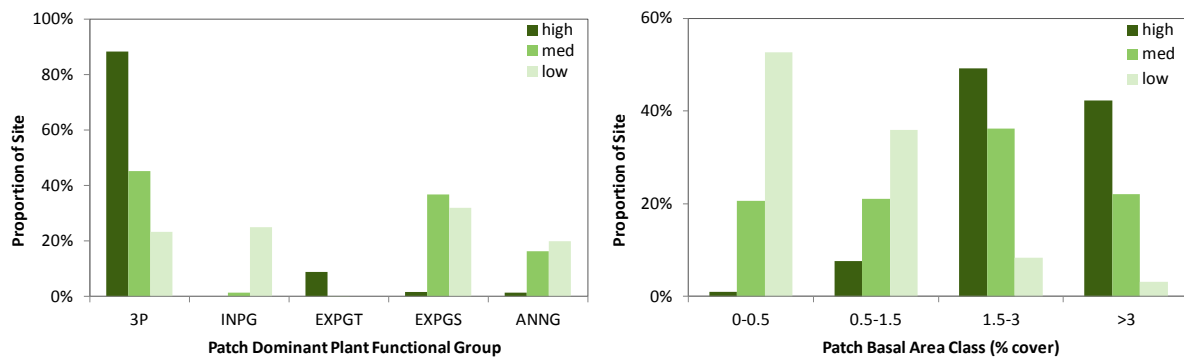


Figure 8. Proportion of plant functional group and basal area across all soil types and cover levels. The functional groups refer to perennial, palatable and productive (3P), increaser perennial grasses under grazing (INPG), exotic stoloniferous grasses being Indian Couch (EXPGS) and annual grasses (ANNG).

The exotic stoloniferous grasses (EXPGS) in both the medium and low cover properties were almost exclusively Indian Couch (*Bothriochloa pertusa*). This grass has the capacity to occupy the available land area following periods of heavy grazing and subsequent native pasture run down, but produces low biomass and dies off during drought periods. Indian Couch is now widespread across the Burdekin catchment and as far south as the Clermont region. The dominance of this grass species is progressively expanding, degrading pasture productivity across a broad area of GBR rangelands. Graziers supported our observations that it is more evident in paddocks that are continually stocked or over stocked.

3.2.4 Landscape Function Analysis

Low-cover sites had considerably lower functional state than medium and high-cover sites based on Soil Surface Condition (SSC) indices (Figure 9). Rainfall was above-average in the first two wet-seasons of this study, and also in prior years. The difference in SSC (and Patchkey) functional indices between high and medium cover classes would become larger

during extended dry periods, particularly in areas dominated by Indian Couch *Bothriochloa pertusa*. For example, medium-cover sites saw a larger decline in the SSC infiltration index in the drier 2013 year (Figure 10). Indeed, the LFA (and Patchkey) monitoring methods appear to over-estimate function in areas dominated by *Bothriochloa pertusa* during above average rainfall years. The total ground cover measurements along transects were generally consistent with the relative differences in long-term GCI for the focus properties. Patch size and changes over time were not correlated with historical cover.

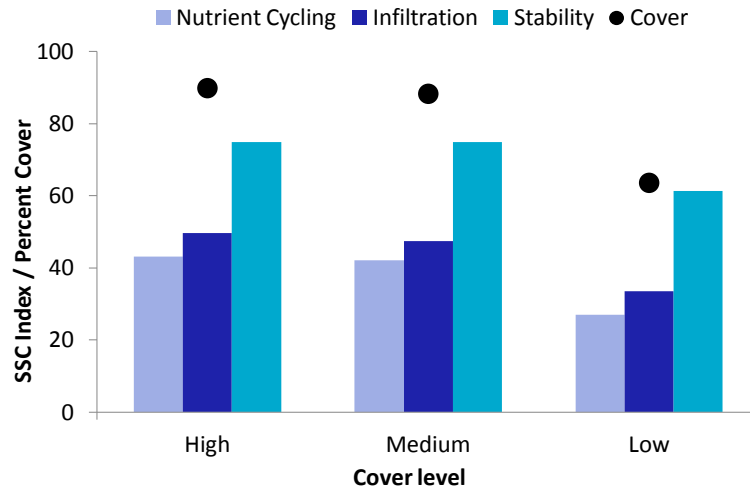


Figure 9 Relationship of Soil Surface Condition indices and surveyed ground cover to property cover class, averaged across three monitoring years and three soil types.

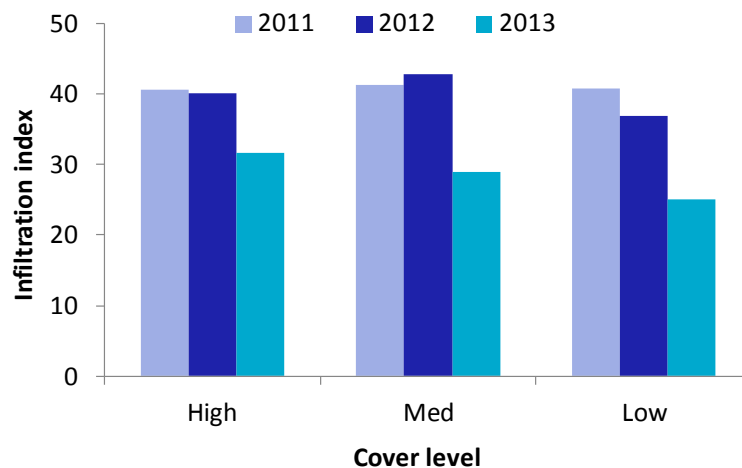


Figure 10 Changes in Soil Surface Condition infiltration index during the study, for Chromosol properties.

3.2.5 Infiltration

There was a clear trend of higher infiltration rate associated with higher historical cover levels irrespective of soil type (Figure 11). Sites dominated by 3P grass species (highlighted in the figure by red borders) are all associated with high infiltration rates compared to the other non-3P dominated sites. Within 3P sites, infiltration capacity was correlated with forage biomass. Higher biomass increases root-zone storage capacity, and the frequency of soil surface macropores. The Chromosol Medium, Chromosol Low and Virginia Park sites are dominated by the stoloniferous and shallow rooted grass species Indian Couch (*Bothriochloa*

pertusa). During wet years, this grass forms a lawn across the landscape which can help to reduce soil erosion, but its shallow roots do not enable much water storage within the soil profile. Even after 10 years of wet-season spelling and reduced forage utilisation at Virginia Park, infiltration capacity remains much lower than at the comparable high-cover property.

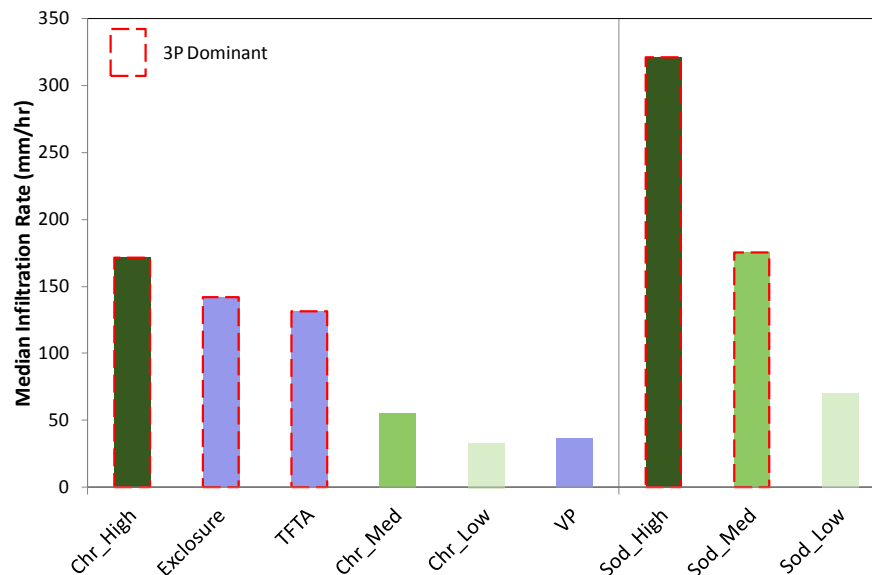


Figure 11 Median soil infiltration capacity measured at the six focus properties in the Chromosol and Sodosol regions, and comparison locations in the Chromosol region.

Plot-scale infiltration capacity was not measured in Vertosol soils due to the large macropores present in this cracking clay soil. However, discussions with the focus property graziers indicated a similar correlation between forage biomass and infiltration for this soil type, with dams requiring much more rainfall to fill when forage levels were high.

3.2.6 Soil movement

The erosion pin measurements indicated that high-cover focus properties had a smaller range of soil movement than low-cover focus properties. In Chromosol soils the average and median values of soil movement were more than 65% lower at the medium cover site and more than 85% lower at the high-cover site, relative to the low-cover site (Figure 12). A similar pattern was observed across the Sodosol properties. These results are consistent with three previous hillslope monitoring studies, which found that reductions in forage utilisation and increases in ground cover resulted in 50% to >70% reductions in hillslope sediment loss (Hawdon *et al.*, 2008; Bartley *et al.*, 2010a; Silburn *et al.*, 2011). The results are also consistent with the Universal Soil Loss Equation, which estimates that increasing rangeland ground cover by 20% reduces hillslope sediment loss by 60–70% (Rosewell, 1993; Thorburn and Wilkinson, 2013).

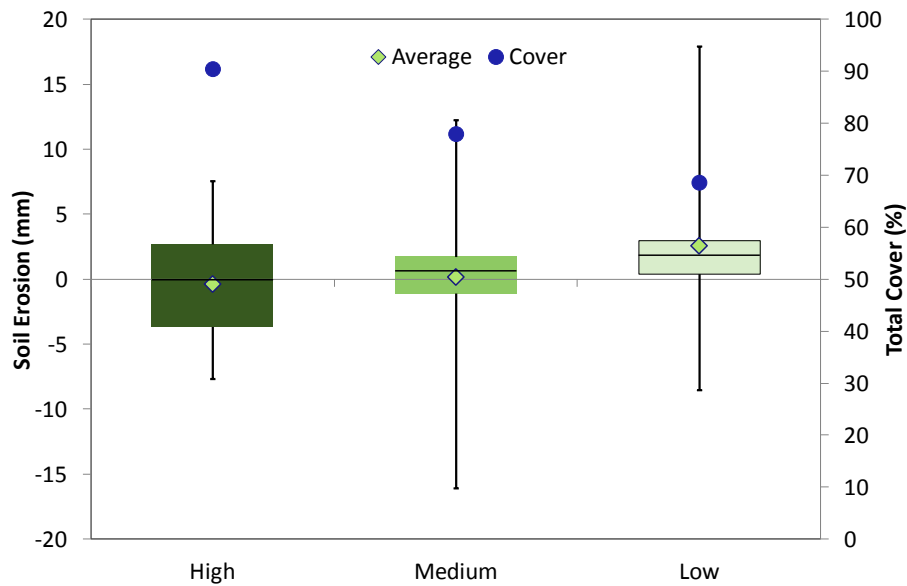


Figure 12 Soil movement and vegetation cover by cover class, for Chromosol soils over the 2012/13 wet season. The solid horizontal lines represent the median values. The box heights represent the 25th to 75th percentiles, and the error bars represent the ranges in measured values.

Black speargrass (*Heteropogon contortus*) was the dominant grass species on the high-cover property which had the lowest soil movement and therefore the most stable state. The medium and low-cover properties (predominantly covered with Indian Couch) had higher rates of erosion and a larger range of soil movement. This contrasts with one previous study, which found higher rates of soil movement on speargrass landscapes compared to *pertusa* landscape (Scanlon *et al.*, 1996). One possible explanation is that the previous measurements were made during the transition to Indian Couch, and that grazing impact was not correlated with 3P dominance during that period.

4 Regional assessment of grazing practice impacts on cover

4.1 Introduction

Spatial assessment of grazing impact on vegetation cover is useful for identifying areas where the impact is most likely to be causing erosion, degrading land condition, and reducing its productive capacity. Remotely-sensed vegetation ground cover as mapped by the Queensland Government's LandsatTM Ground Cover Index (GCI) can be a useful indicator of pasture cover, and hence of erosion hazard. The VegMachine software uses the 25 year time-series of available dry-season GCI images to assess the impact of grazing on cover for a particular property, against the surrounding area or catchment. This type of analysis reveals similar GCI between our focus properties during wetter periods, but large GCI differences during drought periods, of which there were 3 within the period of study (Figure 13). Fire can also influence GCI, although fire effects can be minimised by mapping fire scars and excluding burnt areas from image analysis.

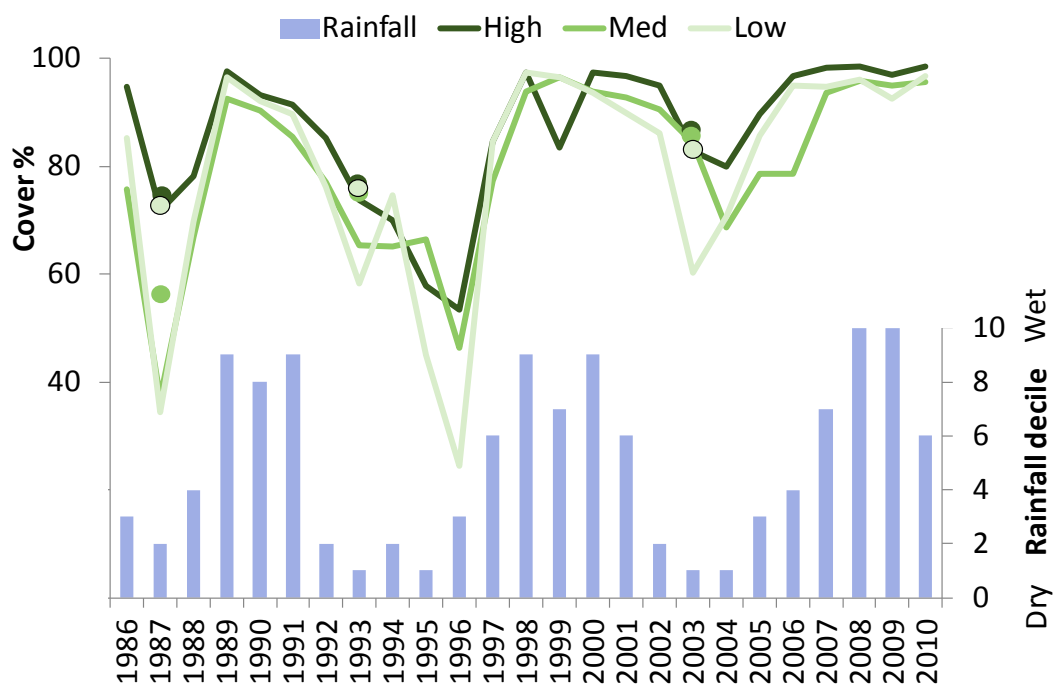


Figure 13: Annual timeseries of ground cover index for three properties in a soil type region. The green points show the DRCM reference cover values for each property in the dry years for which cover deficit was analysed. The blue bars show annual rainfall over the region, as deciles of the long-term average.

One limitation of GCI for regional-scale assessment of grazing impact is that, even in drought years, it also varies spatially in response to rainfall. For example, it is possible that the differences in GCI in Figure 13 are at least partly due to differences in rainfall between the properties. An approach to isolating the management effect from climate gradients is to stratify the analysis area according to land type, and to compare actual cover with that in nearby relatively undisturbed reference areas (e.g. stock-proof exclosures, roadsides, water-

remote areas), that is with the best cover that may be expected in an area during drought periods. This approach has been formalised in the dynamic reference cover method (DRCM), as a largely automated method which estimates the deviation in GCI 'cover deficit' relative to a nearby ~ungrazed or lightly-grazed reference benchmark. Reference areas are defined as those GCI pixels within a surrounding window area that have the most persistent non-wooded ground cover across all GCI images in a multi-year sequence. Persistent ground cover during drier years indicates a resilient and productive rangeland landscape, including low erosion potential and high landscape functionality (Ludwig et al., 1997).

The 'cover deficit' relative to reference pixels can identify management effects when averaged across management units. The DRCM has been previously applied at three sites: (i) a grazing trial where heavy stocking resulted in substantial decline in ground cover in small paddocks, (ii) intermediate scale where wet-season spelling of commercial paddocks resulted in increased ground cover and (iii) individual commercial beef properties where *a priori* ranked condition and trend using ground-based assessment broadly agreed with remote sensing analysis using DRCM. The method has also been recently applied at bioregion scale (Bastin *et al.*, 2014).

In this part of the project, we extended the dynamic reference cover method (DRCM) to enable assessment of spatially-averaged ground cover deficit for each and every property within defined regions. This involved developing guidelines and procedures for applying the method across regions considering known limitations. Secondly we investigated whether changes in property cover deficit over time are related to past grazing practices. There was some commonality of some properties and years of GCI between this project and that used in developing and testing the DRCM method, which provided some confidence in the applicability of the method.

4.2 Methods

4.2.1 Define suitably dry years for cover-deficit analysis

The DRCM analysis requires that suitably dry years of imagery are selected so that grazing impacts on perennial ground cover will be large relative to rainfall effects on ground-cover variation. We selected single years within each of the 3 drought periods for which GCI imagery was available, using the following procedure:

- (i) Grids were prepared of annual rainfall for the October–September period preceding each dry-season GCI image (1987 to 2010). These were accumulated from monthly grids obtained from the Bureau of Meteorology (www.bom.gov.au) at 0.05° pixel resolution (~5 km by ~5 km).
- (ii) October–September rainfall was spatially averaged across each property in each soil type.
- (iii) Property annual rainfalls were converted to percentile rank against the long-term record (1890–2011).
- (iv) The year with the lowest decile (i.e., 10th percentile) in each decade of available GCI imagery (1987–1990, 1991–2000, 2001–2010) was selected.

4.2.2 Calculate cover deficit for selected dry years

Areas with foliage projected cover (FPC) >15%, and areas where tree cover were cleared between 1988 and 2009, were excluded from the analysis since grazing was not the only impact on GCI in these areas (Bastin et al., in prep). In remaining areas the FPC was also subtracted from GCI to produce GCI', as scattered trees and shrubs tend to elevate the GCI estimate of ground cover. This was done using the SLATS time-integrated FPC image product.

The reference ground cover ($GCI_{reference}$) was calculated as a grid, from a grid of the minimum GCI across all years (GCI_{min}), from which FPC had been subtracted (GCI'_{min}). The reference ground-cover for each focal pixel was then calculated as the average of pixels in the 90–95 percentile range of GCI'_{min} within the 1500 pixel square window surrounding each focus pixel (Bastin et al. 2012). This process was repeated as the window was moved across and down that dry year of GCI.

Cover deficit, ΔGC , was then calculated for each GCI pixel in each dry year analysed:

$$\Delta GC = GCI'_{actual} - GCI_{reference}$$

Cover deficit (which generally takes negative values) was spatially averaged across properties of total area >1,000 ha that had >100 ha of the focus soil-type (chromosol, sodosol or vertosol), to give $\overline{\Delta GC}_{property}$.

Change in cover deficit over time ($\Delta \Delta GC$) was also calculated and spatially averaging for each property ($\overline{\Delta \Delta GC}_{property}$):

$$\Delta \Delta GC = \Delta GC_{(t2)} - \Delta GC_{(t1)}$$

4.2.3 Cover-deficit reporting

To identify effective methods for assessing grazing impact using property cover deficit the property spatial-mean values ($\overline{\Delta GC}_{property}$) were reported in three ways:

1. As a ranking of focus properties in each drought year against other properties within the soil type region. This benchmarks property cover against its extended set of neighbours at points in time.
2. As a plot of change in cover deficit between a recent dry year (2003) and an earlier drought (1987). This benchmarks the recent grazing impact on each property against comparable neighbours, considering any dependence on the earlier grazing pressure which may be due to differences in severity between droughts, or different (degraded) pasture composition in properties with historically heavier grazing impact.

4.2.4 Sensitivity analysis

To correctly identify differences in grazing impacts between properties it is important that the property cover deficits are comparable. The GCI may potentially be affected by

differences in soil colour between soil types. In addition, grazing impact can differ between land types (of which soil type is a key determinant) due to soil fertility and tree density. To determine the degree to which property cover deficit was affected by differences in the extent of soil types, $\overline{\Delta GC}$ and $\overline{\Delta \Delta GC}$ for properties in each soil type region were calculated based on:

1. The total area of the property, provided area was $\geq 1,000$ ha ($\overline{\Delta GC}_{\text{property}}$).
2. The area of the focus soil type on each station (chromosol, sodosol or vertosol), only for properties with ≥ 100 ha of that soil type ($\overline{\Delta GC}_{\text{soiltype}}$).

The two cover deficit values for each station were compared to see if differences were significant.

4.3 Results

4.3.1 Dry years selected for analysis

Within the available GCI timeframe (1986–2010), 1987, 1993 and 2003 were the most common driest years in each decade for the focus properties (Figure 14). Across the soil type regions, neighbouring properties had generally less than decile 3 rainfall (30th percentile) in these years, although 1987 was a less-severely dry year in Sodosol and Vertosol regions (Table 4).

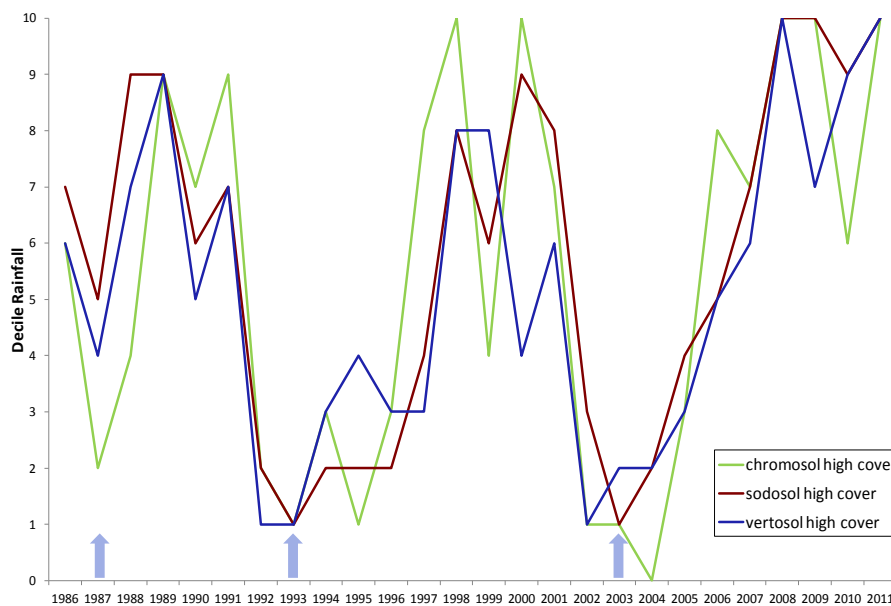


Figure 14. Annual rainfall for high-cover focus properties, as deciles of the long-term average. Monthly rainfall was summed between October and September and ranked against the long-term record (1890–2011). Arrows show the driest year in each decade, in which cover deficit was calculated.

Table 4. The numbers of properties in each rainfall decile, by year and soil type. Rainfall is from October of the preceding year to September of the current GCI year. The numbers for decile rainfall ≤ 3 are in bold.

SOIL TYPE	YEAR	DECILE RAINFALL												TOTAL PROPERTIES	PROPERTIES WITH RAINFALL DECILE ≤3 (%)
		0	1	2	3	4	5	6	7	8	9	10			
Chromosol	1987		40	60	16								116	100	
	1993	6	106	3	1									100	
	2003	1	79	36										100	
Sodosol	1987		8	20	9	17	5	7	2				68	54	
	1993	5	60	3										100	
	2003		42	20	4	2								97	
Vertosol	1987			3	43	48	14	16	2				126	37	
	1993		117	9										100	
	2003		50	42	18	12	4							87	

4.3.2 Isolating grazing impacts from rainfall gradients

The results strongly support the use of cover deficit to isolate grazing impacts from rainfall. Across the 3 soil type regions between Charters Towers and Clermont property mean-annual rainfall varied by more than 200 mm, being generally 500–700 mm/yr (Figure 2). The mean-annual GCI was correlated with the rainfall gradient across the properties, while cover deficit showed no dependence on rainfall (Figure 15). Thus cover deficit can be used to assess grazing impact across a much larger range of rainfall than GCI. The scatter in cover deficit at a given rainfall is due (at least in part) to differences between properties in the grazing impact on cover. Properties with the most negative cover deficits have greatest potential to reduce the magnitude of grazing impact.

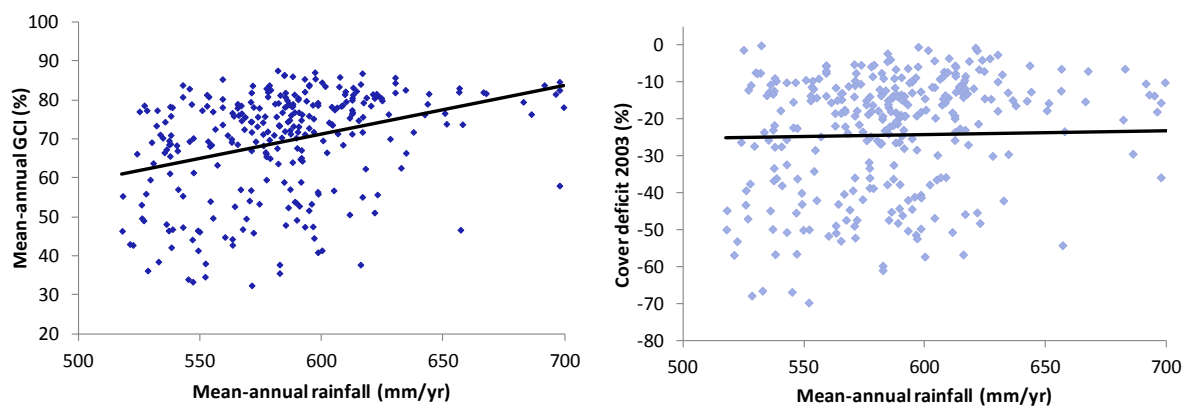


Figure 15. (left) Mean-annual GCI, and (right) cover deficit in 2003 for all properties <700 mm/yr rainfall, across the three soil type regions. GCI displays dependence on rainfall while cover deficit does not.

The absence of rainfall impact on property cover deficit is also illustrated by comparing cover deficit maps (Figure 16) with the GCI map (Figure 2). Differences in cover deficit are evident between adjacent properties and over time, illustrating the management effects.

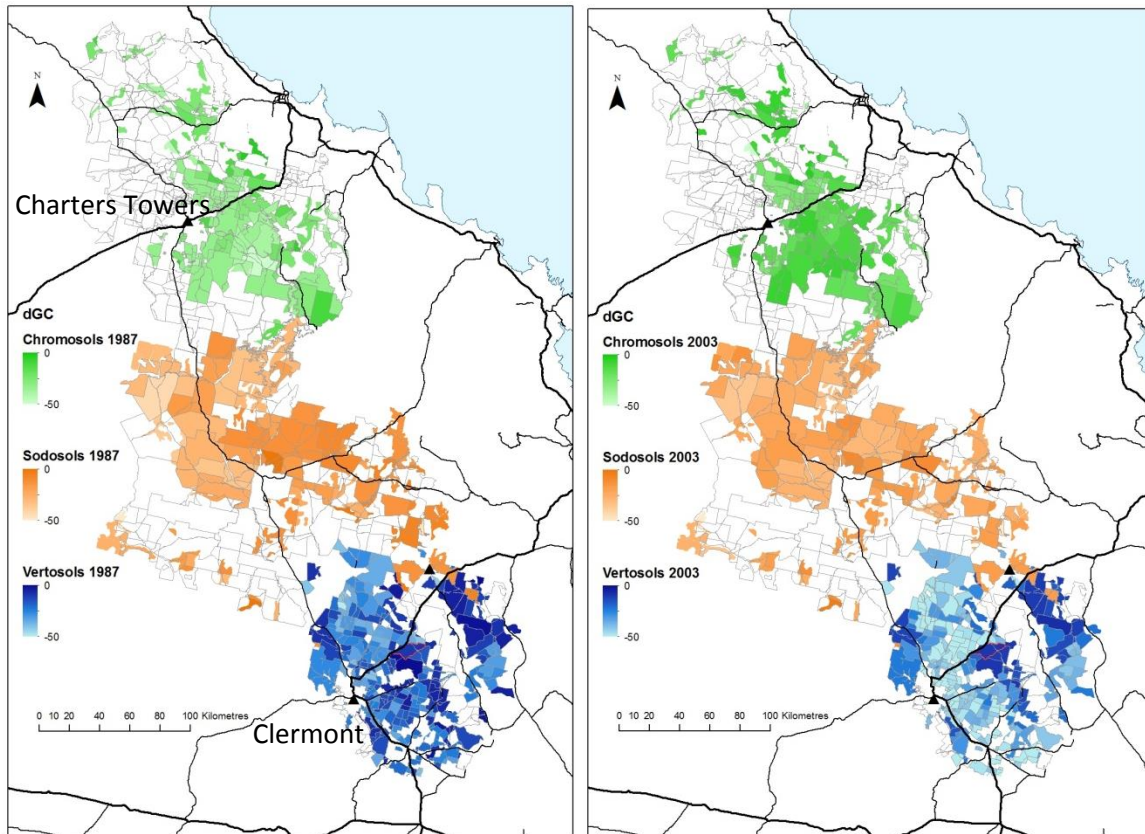


Figure 16: Property mean cover deficit for the three soil type study areas, for 1987 (left) and 2003 (right). For properties with <50% of the focus soil type, cover deficit is shown only over that part of the property. Property boundaries are grey lines.

4.3.3 Sensitivity analysis

Differences in grazing pressure between soil types may be expected due to soil fertility, terrain or pasture type. For properties which had more than half of the area occupied by the focus soil type, $\overline{\Delta GC}_{\text{property}}$ was generally within 5% of $\overline{\Delta GC}_{\text{soiltype}}$, indicating that differences in $\overline{\Delta GC}_{\text{property}}$ between properties could indicate grazing impact. However, below this threshold an increasing mix of soil types meant that soil-type differences more heavily influenced cover deficit comparison between properties (Figure 17). For properties with <50% of a soil type, only the area of that soil type can be accurately compared with other properties of that soil type.

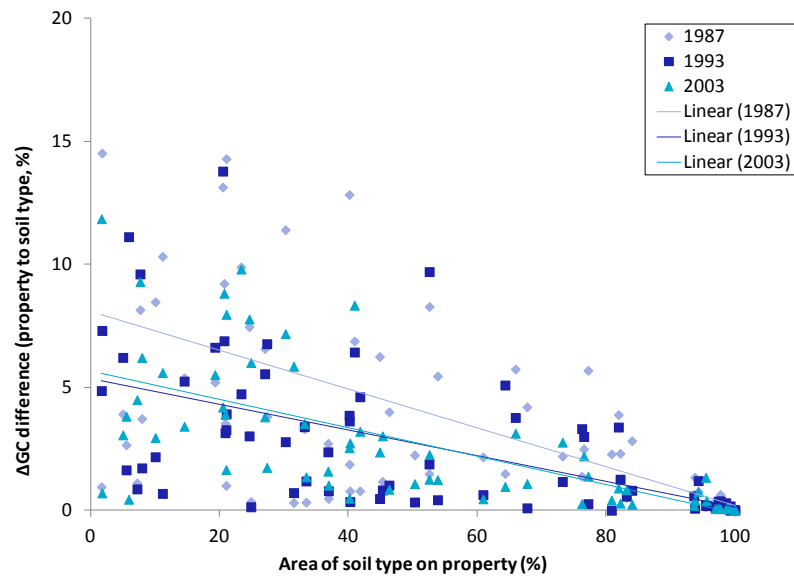


Figure 17. Differences in $\overline{\Delta GC}$ for whole properties relative to the focus soil type area of the properties, at different levels of soil type prevalence.

4.3.4 Grazing impact assessments

The focus properties were selected in reasonable proximity within each soil type region, and therefore they usually had similar levels of reference cover, although this was not the case in all droughts and for all properties. For example, the medium cover property had a much lower reference cover than the high and low cover properties in 1987 (Figure 13).

Cover deficit was strongly dependent on the stocking rates in previous decades, particularly where relative differences in stocking rate were large (Figure 18). The absolute stocking rates resulting in high cover (small cover deficit) averaged 10 animals per km^2 , while those resulting in low cover (large cover deficit) were up to 70 animals per km^2 (Figure 4). The trends with stocking rate were consistent between soil types, even though cover deficit magnitude is also dependent on rainfall, soil and pasture type.

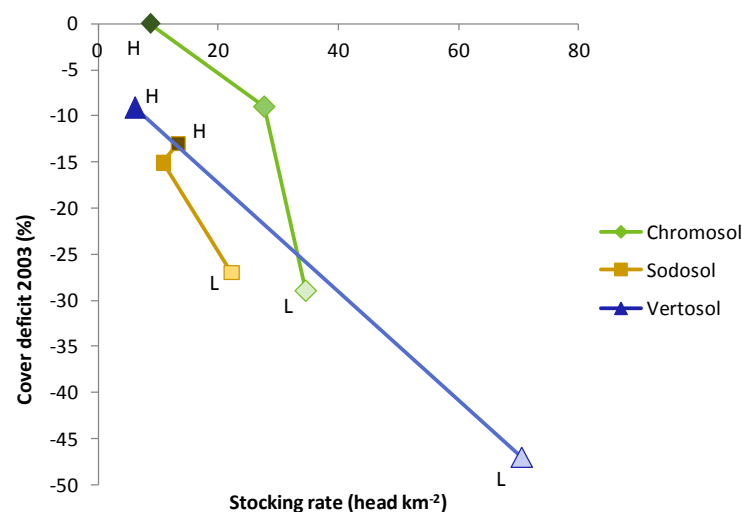


Figure 18. Cover deficit in 2003 on each focus property relative to mean stocking rate in the preceding decade. High cover focus properties (H) had smaller magnitude cover deficit than low cover properties (L) in all three soil types.

The drought average cover deficit indicates the average level of grazing impact over time. The cover deficit can be compared between land parcels of comparable soil and within a region or catchment by expressing as a percentile of all properties (e.g., Table 5).

Table 5. Spatially-averaged cover deficit in dry years, for the soil type area on example properties, as a percentile of all properties >10 km² in each region. Higher percentiles indicate smaller grazing impact relative to other properties.

SOIL TYPE	COVER CLASS OF FOCUS PROPERTY	1987 (%)	1993 (%)	2003 (%)	AVERAGE (%)
Chromosol (n=81)	TFTA (high cover sectors)	80	84	63	76
	TFTA (medium cover sectors)	78	53	88	73
	TFTA (low cover sectors)	86	89	28	68
	Virginia Park (medium cover)	21	21	23	22

The cover deficit percentiles for individual land parcels change between droughts, indicating that cover in difficult seasonal conditions is sensitive to management (Table 5). We found that the change in cover deficit between 1987 and 2003 was dependent on the 1987 cover deficit in Chromosol and Sodosol soil types, with properties having large cover deficit (negative value) in the 1987 drought more likely to show an improvement in cover deficit in the 16-year period to 2003 (Figure 19). This period also included a major drought in the 1990s. This dependence can be attributed to differences in drought severity (a larger cover deficit in 1987 gave more room for improvement), as well as differences in pasture composition (and hence cover dynamics) resulting from past degradation on low-cover properties.

Properties above the trendline have seen a reduction in grazing impact relative to peers, and those below the trendline have seen increasing impact. For example, in 2003, Virginia Park cover deficit plots near to the trendline, indicating that in 2003 it remained representative of many properties which had comparably large cover deficits in 1987. In 2002, wet-season spelling and reduced forage utilisation commenced at Virginia Park (Bartley *et al.*, 2010a; Bartley *et al.*, 2010b). The cover deficit approach presented here will be able to assess the effects of these management changes in a future dry year. In a second example property, the TFTA low-cover property areas had heavier grazing impact in 2003 than its peers in 1987, while the medium cover sectors had smaller grazing impact relative to peers in 1987. This is consistent with the leasehold grazing which occurred on parts of TFTA prior to 2001.

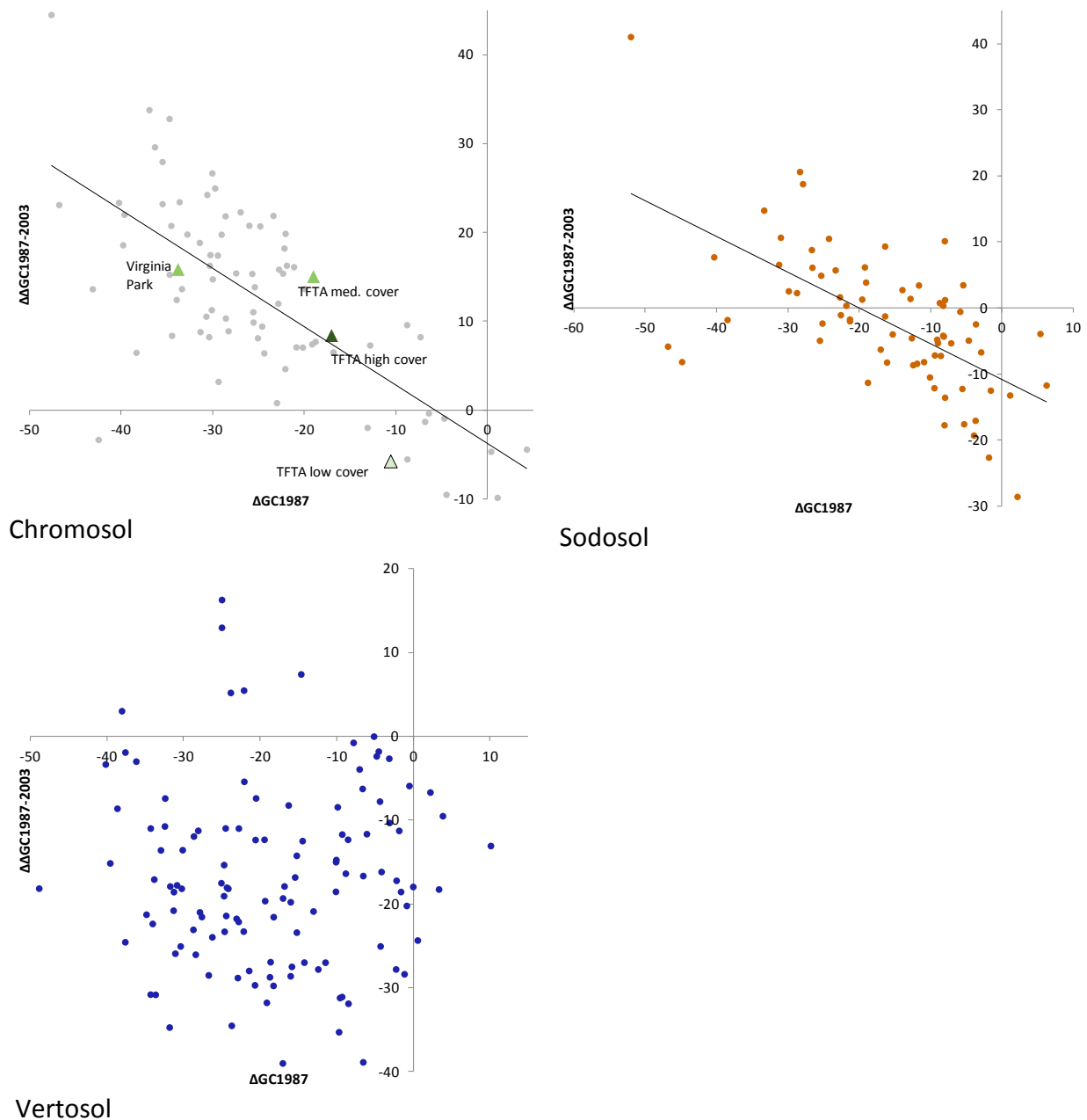


Figure 19. Cover deficit state in 1987 for all properties in each soil type region (x-axis), relative to the change in cover deficit between 1987 and 2003 (y-axis). The dashed lines show significant trendlines.

It is important to note that trendlines in cover deficit state-change plots are simply the mean behaviour of land parcels, and does not necessarily indicate maintenance of land condition. The scatter in cover deficit changes on vertosol properties may be attributed to either more rapid recovery to short periods of heavy grazing on this fertile soil, or broader spatial variation in drought severity relative to other soil types (Table 4). Opportunistic cropping practices may have also contributed to the scatter, despite including only properties nominally mapped as grazing land use (QLUMP, 2004).

The average grazing impact (cover deficit) over the three droughts can be used to identify the relative differences in the potential for improving property cover management. The relative differences between focus properties were as expected based on their differences in

mean-annual GCI (Table 6). The directions of change in cover deficit between 1987 and 2003 relative to other properties (Figure 19), indicates relative improvement, average or relative degradation for each property, such as our focus properties (Table 6). The consistency in rating between the average and change is not surprising given that the focus properties had reasonably stable stocking rates over time.

Table 6. Indicators of grazing impact 1987–2003. The average ranking indicates the average level of grazing impact relative to all properties, while the deviation from trendline indicates change in grazing impact from 1987 to 2003, relative to comparable properties.

SOIL	CHROMOSOL			SODOSOL			VERTOSOL		
Cover	High	Med	Low	High	Med	Low	High	Med	Low
Average grazing impact (relative)	Low	Med.	High	Low	Med.	High	Low		High
Change 1987–2003 (relative)	Impr.	Impr.	Degr.	Impr.	Impr.	Degr.	Impr.		Stable

^A Improvement (reduction) in grazing impact relative to peers

^B Degradation (increase) in grazing impact relative to peers

4.4 Outcomes

Cover deficit calculated from Landsat-derived cover imagery provides an assessment of grazing impact on persistent, perennial cover during three historical drought periods. There is a large scatter in cover deficit between properties, reflecting a wide range of management styles and grazing histories. Properties with large cover deficit have higher potential to reduce grazing impact, and extension activities could be usefully targeted to these properties. Change in pasture composition over time to Indian Couch can mask the effect of grazing on pasture productivity and erosion outcomes, since this grass generates relatively high cover at low biomass levels.

Two metrics are recommended for assessing property grazing impact across regions of consistent soil type:

- Long-term grazing impact can be assessed using cover deficit ($\overline{\Delta GC}$) as a percentile relative to other properties. This metric isolates the long-term impact of grazing on ground cover from rainfall gradients across large regions, and is suitable for identifying the degree of potential each property has for reducing grazing impact (Table 5). It is most indicative of long-term impact when averaged across multiple drought periods.
- Changes in grazing impact between drought periods can be assessed using the deviation from the trendline of change in cover deficit between droughts ($\overline{\Delta \Delta GC}$) plotted against starting cover deficit (Figure 19). This benchmarks change in grazing impact over time against properties of comparable starting state in terms of cover deficit ($\overline{\Delta GC}$). Such benchmarking can be used to evaluate the success of property management at reducing grazing impact on ground cover, associated with public and private investments and change programs such as Reef Rescue. In the Chromosol and

Sodosol regions the starting cover state is often also an indicator of cover dynamics and pasture type, for example replacement of native perennials with Indian Couch on heavily-grazed properties.

Properties with below-average performance in either of these cover deficit metrics have recent grazing impacts larger than the average for the region.

Property mean cover deficit is also sensitive to the mix of soil types (land types) present. When compared between properties having >50% of a common soil type, there is less than 5% uncertainty in differences between properties due to soil type. Cover deficit is only an indicator of land condition. Impacts on soil hydrologic function and pasture productivity (land condition) must be informed by field assessment including pasture composition. The impact of Indian Couch on pasture productivity is investigated further in Section 6.

5 Soil loss responses to increasing ground cover

5.1 Introduction

The relationship between ground cover and hillslope erosion rates is well-established through both measurement (McIvor *et al.*, 1995b; Bartley *et al.*, 2010a; Silburn *et al.*, 2011; Bartley *et al.*, 2014) and modelling (Rosewell, 1993). Reducing grazing pressure should increase ground cover, particularly in drier years, resulting in reduced hillslope erosion. This section quantified that effect.

Because the dependence of erosion on cover is non-linear, and erosion depends also on rainfall, slope and soil type (Rosewell, 1993), the magnitude of response to ground cover change must be estimated over time and in a spatially-explicit way (e.g. 25m pixels within paddocks). Therefore, point measurements of erosion are generally inadequate for comparison between focus properties. This section therefore employed erosion modelling to quantitatively compare erosion rates between the focus properties. The modelling is evaluated by comparison with the site measurements of cover and erosion and prior studies.

We modelled erosion responses using scenarios of improved ground cover for the paddocks on the focus properties where field surveys were conducted. We also modelled scenarios for the whole of each focus property, since the paddocks may not have been representative of properties as a whole. Finally, we modelled the erosion responses over the entire extent of each soil type region, to scenarios of improved grazing management and ground cover. For each scenario we generated an annual time-series of GCI grids, and calculated hillslope erosion rates using the Revised Universal Soil Loss Equation.

5.2 Methods

5.2.1 Estimating GCI under improved grazing practices

The approach we took was to apply the ground-cover distribution of the medium-cover paddocks/properties as the scenario cover distribution for low cover paddocks/properties under improved grazing management. Similarly, the distribution in high-cover paddocks/properties was applied to medium-cover paddocks/properties. This approach was extended to the region using mapping of A, B, C and D land condition categories based on the GCI mean, standard deviation and trend (Karfs *et al.*, 2009). The scenario involved applying the distribution of cover in A-condition areas to country in B condition and B condition cover to C-condition country. It was conservatively assumed that D-condition areas would not improve with altered grazing management alone (i.e. various forms of reclamation also required), and scenario analysis was not performed for these areas. The scenarios were defined in terms of GCI in a 'focus' area being transformed to that in a 'target' area (Table 7).

Table 7. Cover-level pairs used for scenario analysis. Lower cover areas (focus) were fit to higher cover areas (target).

Scale	Soil type					
	Chromosol		Sodosol		Vertosol	
Paddock	Low _{focus}	→ Medium _{target}	Low _{focus}	→ Medium _{target}	Low _{focus}	→ Medium _{target}
	Medium _{focus}	→ High _{target}				
	Virginia Pk _{focus}	→ High _{target}	Medium _{focus}	→ High _{target}	Medium _{focus}	→ High _{target}
Property	Low _{focus}	→ Medium _{target}	Low _{focus}	→ Medium _{target}	Low _{focus}	→ <i>Medium_{target}</i>
	Medium _{focus}	→ High _{target}				
	Virginia Pk _{focus}	→ High _{target}	Medium _{focus}	→ High _{target}	<i>Medium_{focus}</i>	→ <i>High_{target}</i>
Region	Land condition					
	Chromosol		Sodosol		Vertosol	
	C _{focus}	→ B _{target}	C _{focus}	→ B _{target}	C _{focus}	→ B _{target}
	B _{focus}	→ A _{target}	B _{focus}	→ A _{target}	B _{focus}	→ A _{target}

The following procedure was implemented for each year of GCI between 1987 and 2010:

1. Define the GCI cumulative frequency distribution for focus and target areas.
2. Calculate the cumulative fifth percentile values of GCI for all distributions (i.e. 5th, 10th, 15th, 90th, 95th and 100th percentile values).
3. Graph 5th percentile values for the target vs. the focus, and fit suitable regression functions (linear and natural log) (Figure 20).
4. Select the fitted function with the higher coefficient of determination (R^2) and minimum extent of prediction outside the range 0–100%. The performance of the fitted function was also assessed in terms of the visual match between the cumulative frequency distribution between the output focus scenario and the target.

The selected function was used to predict the pixel-level scenario GCI for each year. The GCI_{focus} was retained untransformed in rare situations; where the 5th percentile values of GCI_{focus} exceeded GCI_{target} , and where mean of GCI_{focus} exceeded GCI_{target} .

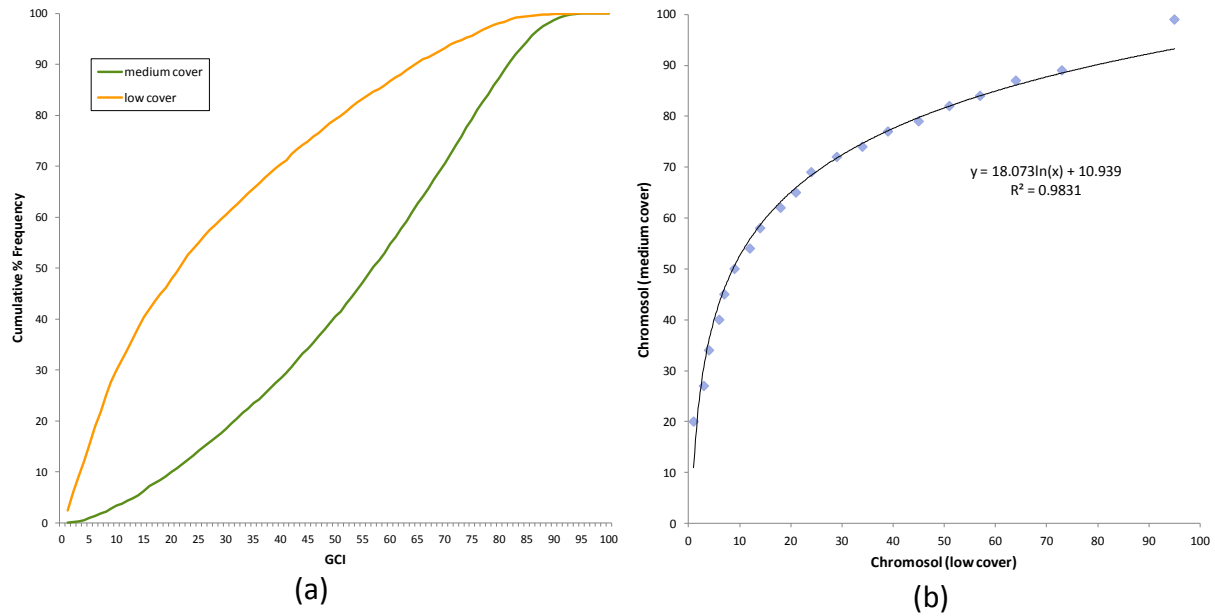


Figure 20. (a) Cumulative frequency distributions for example low cover (focus) and medium cover (target) properties. (b) Target versus focus property GCI for five-percentile increments in the distributions, and a natural log line of best fit used for applying the target distribution to the focus property.

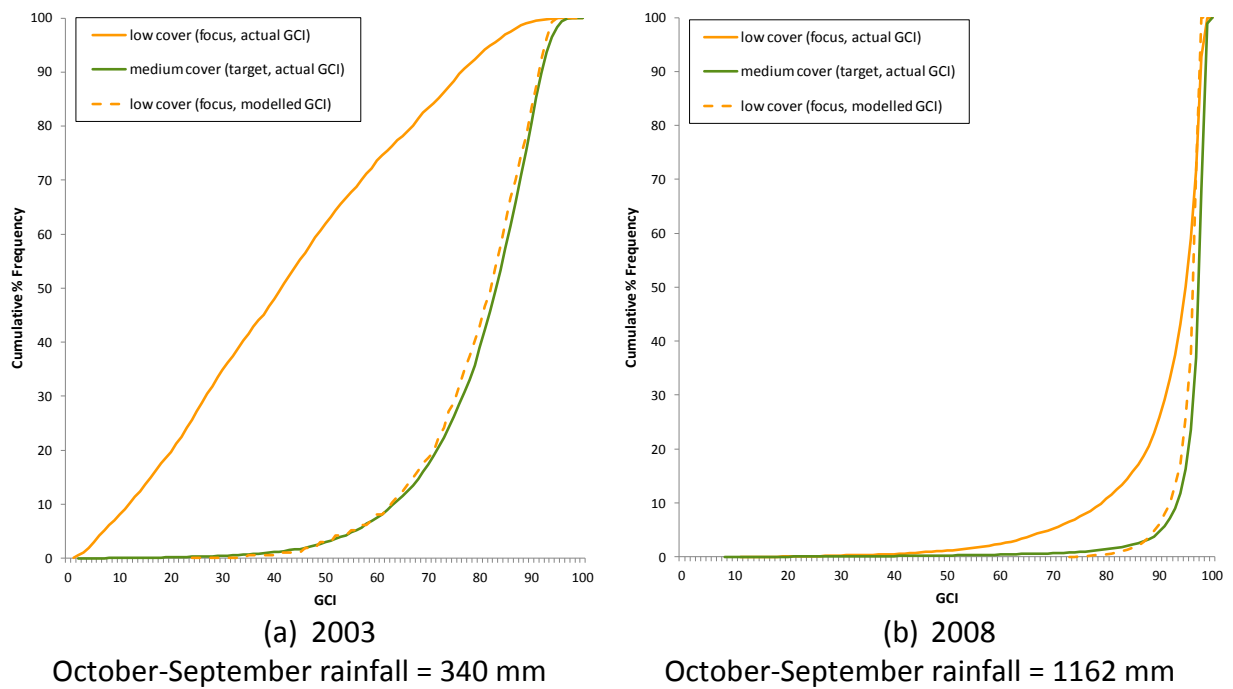


Figure 21. Cumulative percentage frequency distributions GCI for a low-cover paddock (focus) modelled against the medium-cover paddock (target) for (a) a dry year, and (b) a wet year. The actual GCI frequency distribution of the focus paddock is also shown for comparison.

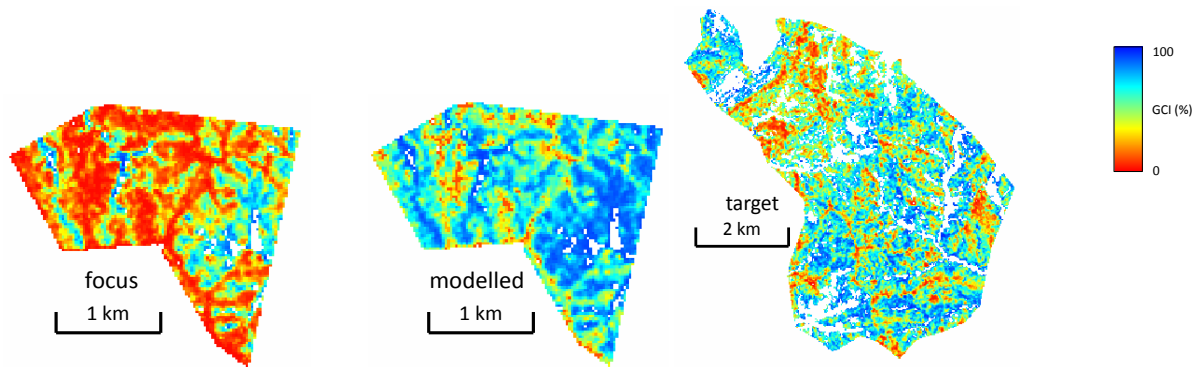


Figure 22. Example of cover scenario modelling. The left image is GCI in a low-cover focus paddock in a dry year. The right image is GCI in that year for the medium-cover paddock in that year and soil type, from which the scenario cover distribution was derived. The middle image shows the resulting scenario cover grid for the low-cover paddock. White areas within each image represent woody cover (FPC > 20%) where scenario GCI and erosion were not calculated.

5.2.2 Calculating erosion rates under cover scenarios rainfall erosivity, terrain slope and soil erodability

Hillslope sheetwash and rill erosion was estimated using the Modified Universal Soil Loss Equation (MUSLE; Williams and Berndt, 1977):

$$E_i = RKLSCP \quad \text{Equation 1}$$

Where the right hand side factors represent rainfall erosivity (R ; units $\text{MJ mm ha}^{-1}\text{hr}^{-1}\text{day}^{-1}$), soil erodability (K ; units $\text{t ha hr ha}^{-1}\text{MJ}^{-1}\text{mm}^{-1}$), slope length and gradient (L , S), vegetation cover (C) and erosion control practices (P) such as crop terracing. Each factor was estimated as a grid across the 3 regions. The R factor was estimated as a function of daily rainfall and time of year (Yu, 1998). The rainfall data were derived from the AWAP project (Jones *et al.*, 2009). The remaining factors were estimated using standard methods (Renard *et al.*, 1997). The K factor was derived from soil mapping (Brough *et al.*, 2006). The slope length and gradient were derived from the 1 second SRTM DEM, which provides superior slope estimates to contour-interpolated DEMs (Kinsey-Henderson and Wilkinson, 2013). The C factor was estimated from the annual GCI grids, both as experienced and after transforming to the improved cover scenario as described in the section above. The P factor was set to 1.

5.3 Scenario results

The scenario results from erosion modelling indicated that large reductions in stocking rates can lead to large reductions in hillslope erosion. The paddock scenarios generally resulted in cover increases of 5–15% and reductions in mean-annual gross hillslope erosion of 35–60%. As expected, the reductions in erosion were generally larger in those scenarios with the largest magnitude of cover change (Figure 23). At property scale the cover increases were generally smaller, resulting in smaller but still considerable reductions in mean-annual gross hillslope erosion of 19–29% across Chromosol and Sodosol soil types (Table 8). Absolute erosion rates were influenced by terrain slope and rainfall as well as cover.

Applying A-class cover to areas of B-condition, and B-class cover to areas of C-condition resulted reductions in hillslope erosion rate of 32–46% at regional scale (Table 8). The Vertosol C-condition region had a larger proportional reduction, probably due to the historical cover having areas of very low cover associated with opportunity cropping. The scenario reductions in erosion were similar across B-condition and C-condition areas.

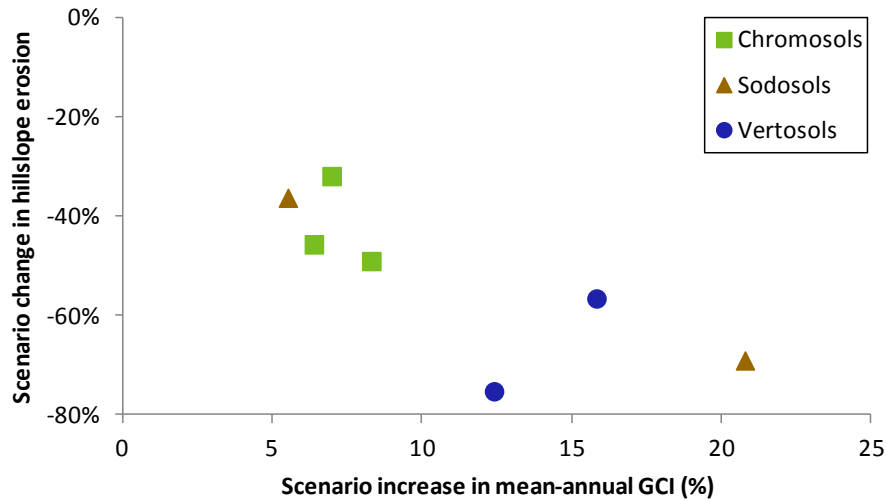


Figure 23. Modelled reductions in hillslope erosion associated with scenarios of increasing cover on low cover focus properties, to match the cover distributions on medium cover focus properties, and increasing medium cover properties to high cover. Data are averaged across the paddocks where field monitoring occurred on focus properties.

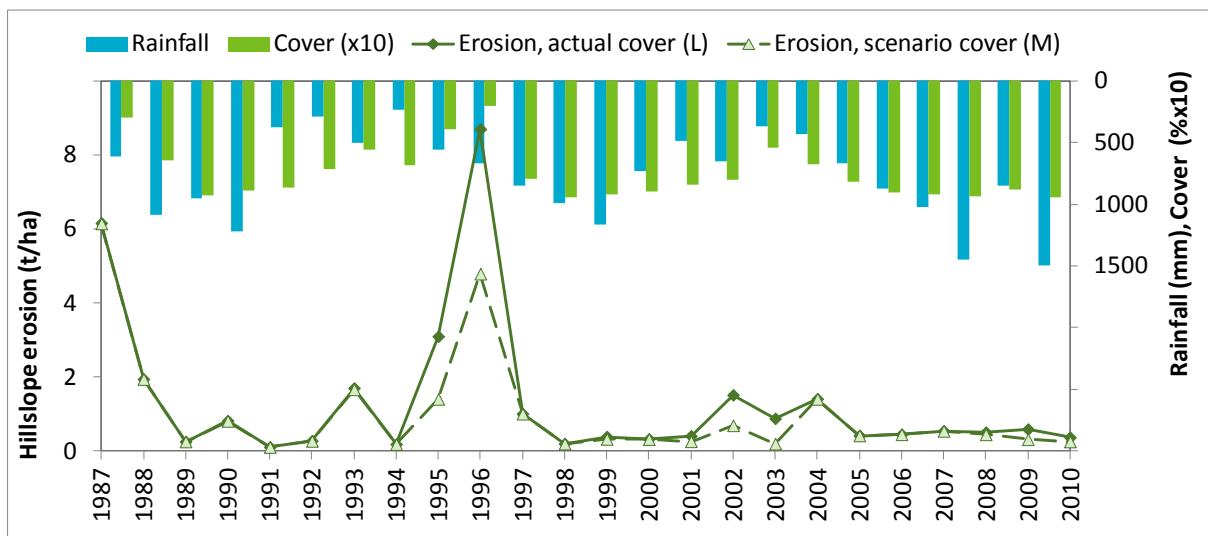


Figure 24. Timeseries of annual mean gross hillslope erosion for a low cover focus property modelled using the Revised Universal Soil Loss Equation, under actual cover and under a medium cover scenario.

Table 8. Percentage reductions in mean-annual gross erosion rate for scenarios of improved ground cover

SCALE	SOIL ^A	COVER SCENARIO ^B	EROSION			CHANGES IN COVER (%)		
			ACTUAL COVER (T/HA/YR)	SCENARIO COVER (T/HA/YR)	CHANGE (%)	MEAN-ANNUAL	DROUGHT MEAN ^C	DROUGHT MAX.
Paddock	Chrom.	L → M	1.8	1.2	-32	7	24	37
	Chrom.	VP ^D → H	1.2	0.7	-46	6	20	23
	Chrom.	M → H	1.4	0.7	-49	8	21	34
	Sod.	L → M	0.6	0.2	-69	21	25	57
	Sod.	M → H	2.8	1.8	-36	6	16	22
	Vert.	L → M	1.6	0.7	-57	16	22	38
	Vert.	M → H	0.8	0.2	-75	12	33	55
Property	Chrom.	L → M	1.3	1.0	-24	4	16	26
	Chrom.	M → H	1.3	1.0	-25	4	11	29
	Sod.	L → M	0.4	0.3	-29	6	7	15
	Sod.	M → H	2.5	2.0	-19	3	9	18
	Vert.	L → M	2.7	0.4	-85	31	43	48
	Vert.	M → H	1.0	0.5	-50	7	15	24
Region	Chr.	C → B	1.4	0.8	-44	7	15	20
	Chr.	B → A	1.4	0.9	-32	5	11	18
	Sod.	C → B	0.9	0.5	-46	8	14	17
	Sod.	B → A	1.4	0.8	-44	7	15	20
	Vert.	C → B	1.0	0.4	-60	11	18	21
	Vert.	B → A	0.6	0.3	-43	6	11	15

^A Chromosol, Sodosol and Vertosol.^B L = Low, M = Medium, H = High, A/B/C = condition classes (Karfs *et al.*, 2009).^C The maximum annual difference in drought ground cover between scenario and historical time-series, averaged across 1987, 1993 and 2003.^D Virginia Park, Bottom Aires paddock.

The timeseries of predicted erosion was consistently highest in years of lowest cover and median or moderate rainfall, rather than the years of highest rainfall, due to the sensitivity of erosion to ground cover (e.g., Figure 24). Often very wet years occur within a run of reasonably wet years which allow cover to build up, thus moderating the erosion in those years. Previous field monitoring supports the predicted sensitivity of erosion to cover (McIvor *et al.*, 1995b; Silburn *et al.*, 2011). Therefore, maintaining ground cover through drought periods is very important for reducing long-term hillslope sediment loss.

The modelled scenario reductions in gross hillslope erosion are smaller than those indicated by differences in soil movement between sites measured using erosion pins (Section 3.2.6). The modelled scenarios are also likely to be conservative estimates of the associated reductions in hillslope sediment loss to streams. This is firstly because the efficiency of sediment delivery (the hillslope sediment delivery ratio) also reduces with increasing cover levels (Verstraeten *et al.*, 2007). Secondly, the because the 25 m resolution of the Landsat-derived GCI product does not represent small bare areas (scalds), which are more prevalent at lower cover levels (Appendix 2), and can contribute large proportions of total hillslope

sediment loss (Bartley *et al.*, 2010b). This means that actual erosion rates at low cover levels can be under-estimated when using the GCI cover data (Wilkinson *et al.*, 2014). Reduced stocking rates and wet-season spelling have been observed to result in re-establishment of some vegetation cover on scalds within a decade (Bartley *et al.*, 2010b). Grazing exclusion can also see similar responses within several years (Connolly *et al.*, 1997).

Some limited local field data confirms that measured reductions in hillslope sediment loss associated with reduced stocking rates can be larger than the scenario estimates. Firstly, the introduction of reduced forage utilisation and wet-season spelling resulted in an 80% reduction in hillslope runoff TSS concentration (Bartley *et al.*, 2010a), almost twice the 46% estimated reduction in gross erosion from a transition to high cover levels (Table 8). Another previous study on Chromosol soils indicated that removing grazing completely reduced hillslope sediment yield by more than 50% relative to a grazed (and much lower cover) adjacent hillslope (Hawdon *et al.*, 2008). Changes in soil infiltration capacity may reduce runoff volumes and contribute to further reductions in hillslope sediment loss in the long-term.

6 Forage productivity drivers and scenarios

6.1 Introduction

As with the remote sensing and field work, the broad aim of the grass production modelling was to explore the relationships between land management, pasture cover, and pastoral productivity. Since numerous factors differ between sites (weather, physical soil characteristics, land condition, management etc.) it is usually difficult to interpret the exact causes of observed cover differences between sites.

We used simulation modelling to 1) extrapolate the short-term field observations from the project to longer time frames; 2) run controlled scenarios that could explore mechanisms of response and implications of changes in pasture cover; and 3) evaluate what changes in pasture cover mean in terms of land condition and productivity.

6.2 Methods

6.2.1 GRASP calibration and simulation of focus properties

To model pastures and productivity we used the GRASP pasture systems model (Rickert and McKeon, 1988; McKeon *et al.*, 1990), the main pastoral model used across Australia's tropical rangelands. The GRASP model was first calibrated for the nine focus study sites (3 land types x 3 cover levels, as described in Section 2). Initial soil and vegetation surveys of each site were used to derive parameters for vegetation structure and plant physical characteristics, depths of different rooting layers, and water holding characteristics of those layers (based on estimates of soil texture). Daily weather data for each site was obtained from the SILO database (Jeffrey *et al.*, 2001).

Crucial parameters on pasture growth and the amount of nitrogen available for plant growth (some of the most fundamentally important GRASP parameters) were collected on the high, medium and low cover focus properties, using grazing exclosures to exclude interference from grazing animals. There were only sufficient project resources to make these exclosure measurements on one soil type, and the Chromosol sites were chosen because these land types are increasingly being invaded by the creeping exotic grass, *Bothriocloa pertusa* (Indian couch). There are currently no good parameter sets for representing *B. pertusa* pastures in GRASP, and understanding how their productivity differs from native pastures will assist in developing management options. Furthermore, in a concurrent project we were working to improve GRASP modelling of runoff and erosion on a nearby Chromosol site at Virginia Park (Stokes and Wilkinson, 2013), where additional field data were available (Bartley *et al.*, 2010a; Bartley *et al.*, 2010b; Bartley *et al.*, 2013). Improvements in parameter fitting were shared between these two projects.

Five exclosures were erected at each site, located adjacent to the transects used for the PatchKey and LFA field assessments (Section 3). Three 0.5 m x 0.5 m quadrats were marked in each exclosure. Quadrats were clipped in October 2011 and the regrowth clipped again at the peak of the growth season in April 2012 to measure pasture production. There was a very good wet season in 2011/12, so the measured growth in April 2012 would be close to

the maximum possible in good years. Repeat regrowth measurements were made in May 2013.

The nitrogen content of exclosure forage growth was analysed using near-infrared spectroscopy (NIRS; Shenk and Westerhaus, 1994) at the CSIRO laboratory in Floreat (WA). Results were used to calculate two fundamentally important GRASP parameters: (a) the maximum dilution of plant nitrogen, expressed as the lowest nitrogen concentration that forage can get down to, at which point growth ceases (Parameter p99) and (b) the total pool of nitrogen available for plant growth, measured as the total amount of nitrogen per unit area that was in the grass sward at the end of a wet and productive season (Parameter p101). In GRASP modelling, the ratio (b)/(a) limits the amount of forage that can be produced in a good growing season. In addition, the data are of interest by themselves for understanding the impacts of land management on land condition and forage production.

Records on stock numbers for study site paddocks were obtained from interviews with participating landholders (Section 3.2). There was a substantial difference in the quality of the records among sites, with some sites having written records of all stock movements in and out of individual paddocks for many years, and others having a more general indication of average stocking rate over the past few years. We therefore converted all records to a long term average set stocking rate in the modelling, rather than trying to represent changing stocking numbers over time within sites.

Other site parameters required by GRASP were estimated indirectly, using the above data and other sources.

Simulations over the past 25 years (matching the period of available GCI data) were run using the recorded fixed stocking rates and site parameter sets for each site, with dynamic degradation turned off (to represent only the short-term effects of grazing and seasonal variation over the past few decades). Simulated end-of-dry-season (November) cover estimates were compared against independent satellite observations Ground Cover Index (GCI) from Section 4 to give an indication of the reliability of the models. Simulation modelling concentrated on Chromosol sites, where most data was available to calibrate, test and provide confidence in the simulations.

6.2.2 Scenario modelling of grazing management and land condition

The calibrated model was used to identify the contributions of various factors to cover differences between sites, by comparing scenarios with controlled factorial combinations of factors. All parameters (such as weather data and soil physical properties) were kept the same between scenarios, except for the following four factors:

- Land condition, denoted A (good) and C (poor), was represented using nitrogen and grass basal area parameters from contrasting Chromosol focus properties.
- Pasture type contrasted native tussock pastures with *B. pertusa* pastures. These were represented by differences in plant structure and leaf detachment rates, as derived from the focus property measurements and parameter sets.
- Stocking rate was set as a target average utilization rate, i.e., the proportion of forage growth consumed by livestock each year. A safe sustainable level was defined at 20%

utilization rate, which is often used in developing grazing management recommendations. A heavy (unsustainable) stocking rate was defined at 40% utilization rate. Fixed stocking rates (units per ha) corresponding to these utilisation rates were derived from the average annual pasture growth.

- For flexible stocking, feed budgeting was used where animal numbers were adjusted each June based on targeting a proportion of available forage to be utilised. We acknowledge that there are practical limitations on pastoral enterprises (e.g., maintaining herd structures) that at times would limit making adjustments as large as were modelled in this simple representation.

Table 9. Scenarios used to explore the contributions of four factors, in combination with annual variation in weather, to changes in grass cover. The option associated with better pastures and management is marked in bold with a green background. Stocking rates are expressed as mean percentage utilization of annual grass growth.

SCENARIO NAME	LAND CONDITION	PASTURE TYPE	UTILISATION RATE	STOCKING STRATEGY
Reference (Good)	A	Native	20%	Flexible
Poor (ALL)	C	<i>B. pertusa</i>	40%	Set stock
Poor +SR	C	<i>B. pertusa</i>	20%	Set stock
Poor +Flex	C	<i>B. pertusa</i>	<40% (26%)^A	Flexible
Poor +Native	C	Native	40%	Set stock
Poor +Native +Condition (= Reference –Management)	A	Native	40%	Set stock

^A The model automatically reduced stocking rates due to forage running out, which reduced the average utilisation over the modelling period.

Based on the above factors, a reference (good) scenario was defined where all four factors represented better pastures and management (A condition native pastures, with flexible stocking targeting 20% utilization) (Table 9). These were contrasted against a 'Poor (ALL)' worst case scenario (C condition *B. pertusa* pastures with set stocking at 40% average utilization).

The individual contributions of each factor between the two extreme scenarios were identified using a set of simulations that made sequential improvements to the 'Poor (ALL)' scenario;

- Improved stocking rates (Poor +SR)
- Improved stocking strategy (Poor +Flex).
- Changes in vegetation composition (Poor +Native)
- Changes in both composition and land condition (Poor +Native +Condition) *without* improvements in management. This scenario is the same as same as the 'reference (good)' scenario with the poorer management options.

The scenarios were run over 125 years with dynamic degradation turned off, so that models represented just the immediate effects of management under the weather conditions of each year (without the long-term effects of management that carry over from year to year through gradually affecting land condition).

6.2.3 Scenario modelling of pasture recovery

Forage utilization rates vary between years due to weather and pasture growth fluctuations, as well as changes in stock numbers. Forage productivity declines during dry periods or when forage is over-grazed, and it recovers during periods of lower grazing pressure. Potentially, land condition can become degraded if the rate of recovery is too slow to build up forage prior to the onset of the next dry period. Rates of recovery in pasture productivity are uncertain, with little suitable data to calibrate and validate analyses.

We used grass production modelling to investigate what effect differences in land condition recovery rates have on the way pastures respond to land management. Directly measuring the effects of different grazing strategies on long-term land condition outcomes was not possible within the duration of the study.

Previous grass production modelling has estimated rates of recovery to be similar to rates of degradation. However, we have shown that recovery in productivity often requires recovery of 3P pasture composition, soil infiltration and nitrogen pool. Therefore, we explored the implications of slower recovery rates by modelling scenarios of the maximum rate of recovery being about the same as the maximum rate of degradation (previous assumption), and rates of recovery $1/3^{\text{rd}}$ and $1/6^{\text{th}}$ that of the degradation rate.

Land started in 'B' condition, and a range of fixed stocking rates (1–36 AE/km²) were applied to test the effectiveness of stocking rate management in improving land condition under the different recovery rate scenarios. Simulations were run for 125 years. The average land condition (quantified as the simulated percentage of perennial 3P grasses) and average productivity (quantified as simulated live weight gain per ha) over the simulation period were calculated for each scenario and plotted against stocking rate.

6.3 Results

6.3.1 GRASP calibration and simulation of focus properties

Land degradation has reduced the pool of available nitrogen for plant growth at the low-cover focus property (Figure 25), limiting the amount of forage that can be produced (Figure 26). Forage protein (rather than the amount of forage *per se*) that is the main constraint on animal production in tropical pastures (more-so than forage biomass). The higher availability of nitrogen in good condition pastures allowed them to produce about double the amount of protein of poorer pastures. Higher nitrogen in pastures also leads to reduced nitrogen loss into runoff.

At sites in poorer land condition, the quality of the smaller amount of forage present was improved, in terms of higher nitrogen and protein levels, and increased digestibility (Figure 25). *Bothriocloa pertusa* pastures were also structurally very different from native pastures in that they had substantially lower standing biomass at the same cover (Figure 27).

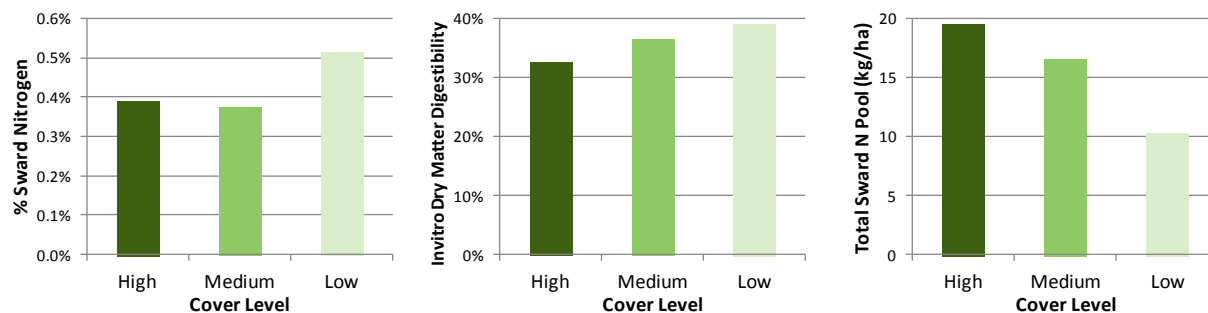


Figure 25. Forage nitrogen data for the grass sward in enclosures on Chromosol soils for the three focus properties differing in ground cover level and management histories. Data are for a) nitrogen content of grass sward, b) IVDMD (in vitro dry matter digestibility), and c) the total nitrogen pool in the grass sward (at the peak of the growth season in a very good growth year, April 2012).

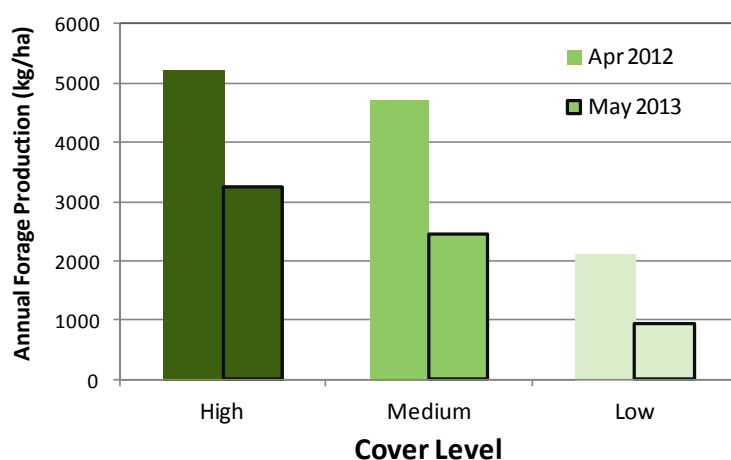


Figure 26. Forage production (growth) from quadrats in grazing enclosures on Chromosol soils for the three focus properties differing in ground cover and management histories. Production was measured by clipping all forage in ~October prior to each growth season, and then harvesting at the end of each growth season in April 2012 and May 2013.

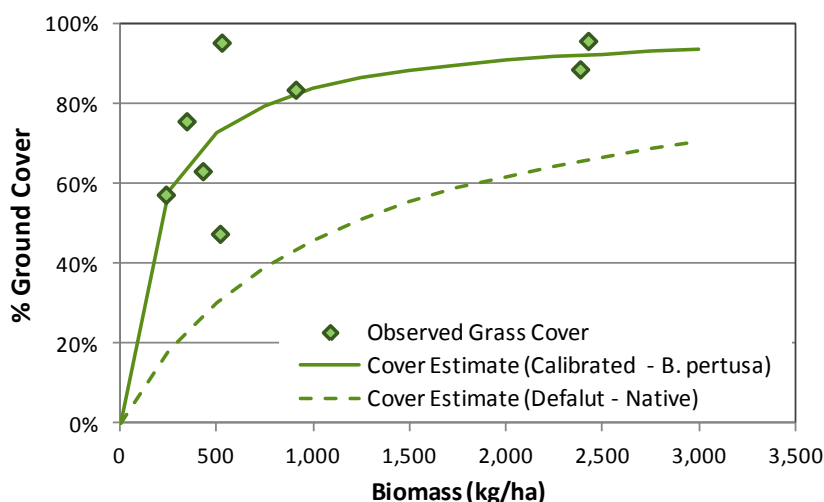


Figure 27. Contrasting relationships between grass cover and biomass for pastures dominated by *Bothriocloa pertusa* (solid line and diamonds) and typical native pastures with tussock grasses in the region (dashed line). The diamonds are actual field observations and the solid line is the fitted curve (in the form of the equation used in GRASP). The dashed line is the parameterized curve for native tussock grasses on similar soils. Note that at 50% cover, the *B. pertusa* pastures have less than a quarter of the standing biomass of a native pasture with the same cover.

The patterns in modelled pasture cover of focus properties closely matched independent measures of cover from satellite data over the past 25 years, declining to similar levels during the three drought periods (e.g., compare Figure 28a and Figure 13). In wetter periods, GRASP cover estimates were limited to <80% because they represent only the cover of pasture grasses, whereas the GCI measurements included additional cover from non-grass species and litter, and would have included the effects of any changes in stock regimes between years. Despite strongly contrasting management between the sites, modelled pasture cover was very similar except during drought.

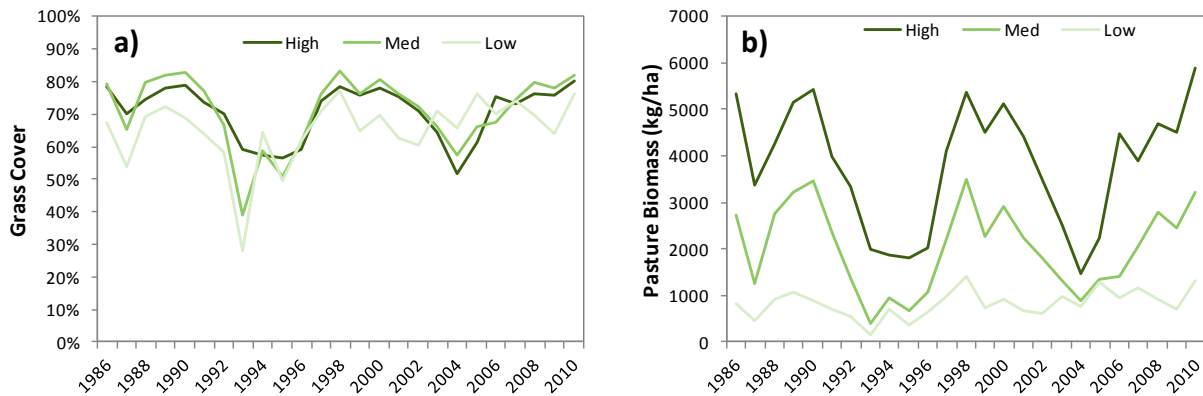


Figure 28. Modelled results for the Chromosol focus paddocks, using stocking rates consistent with the average reported by property land holders, and model forage parameters based on exclosure measurements during the project. Data are a) modelled pasture cover, and b) modelled pasture biomass (all at the end of the dry season each year).

A key finding was that differences in pasture biomass and productivity were far more profound than measurements of cover alone might suggest (Figure 28b). Over the past 25 years, medium cover properties had more than twice the median pasture biomass of low-cover properties, and high cover properties more than four times the median biomass. A key difference was the invasion of Indian Couch (*Bothriochloa pertusa*) as pastures degrade, which has high canopy cover per unit biomass. This change in pasture composition has potentially led to cover remote sensing creating an exaggerated expectation of how quickly pastures can recover from degradation.

The models suggested that short-term animal productivity (per ha) was greatest on the low-cover site, but only because this was being stocked at more than double the rates of utilization which were sustainable in the long-term, as indicated by the change in cover deficit over the period 1987–2003 being well below the trendline fitted to all properties in the region (Figure 19a). Modelling safe utilization rates across all properties (grazing 20% of pasture grown each year) resulted in highest animal productivity (per ha) on the high-cover site, and lowest on the low-cover site.

6.3.2 Scenario modelling of grazing management and land condition

Cover in the Poor (ALL) scenario was much more influenced by the quality of growth season than in the Reference scenario (Figure 29a). This indicates that changes in cover deficit from one drought to the next will be strongly influenced by the differences in qualities of the growth seasons between and during those particular droughts.

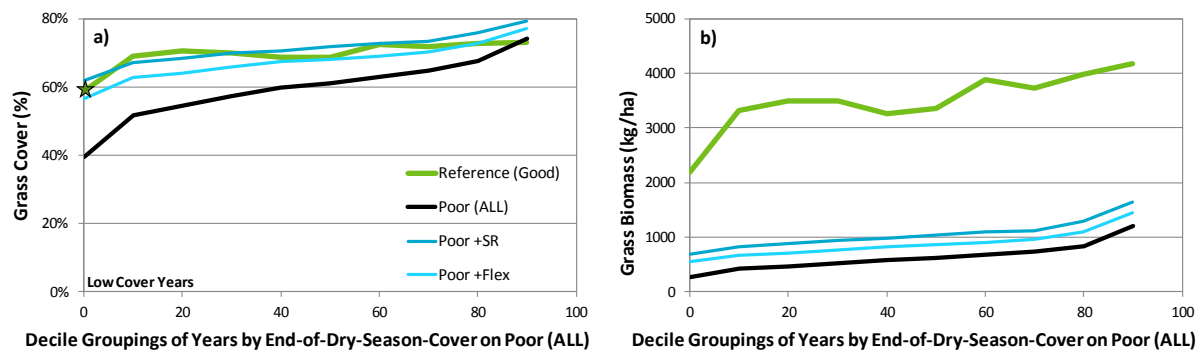


Figure 29. Within-season effects of changes in management on end of dry season (November) a) cover and b) biomass across a range of differing qualities of growth seasons (represented by decile groupings of the 125 years of simulation according to the level of cover in the Poor (ALL) scenario).

We also found that dry-season cover levels are more sensitive to grazing pressure in that immediate year, resulting from the applied stocking rate and quality of weather in the particular year, than by the underlying land condition or pasture composition. In most years, including dry years, cover can be improved to nearly reference levels by reducing stocking rates, even on poor condition Indian Couch (*B.pertusa*) pastures (Poor +SR), or by using flexible stocking rates (Poor +Flex; Figure 29a). Cover in poor growth (dry) years was also little influenced by pasture composition and condition (Poor +Native +Condition; Figure 30a). The dependence of cover on recent grazing pressure is consistent with the large changes in cover deficit percentile between droughts seen on most focus properties (Table 5).

Pasture biomass does not recover towards reference conditions through short-term changes in management (Figure 29b). Instead, biomass is more heavily influenced by long-term grazing management and land condition (Figure 30b). Following reduction in stocking rate, biomass can be expected to progressively improve towards reference levels, as condition and composition improve in the long-term. Responsive stocking strategies that use forage budgeting had some benefit relative to set stocking at high stocking rates.

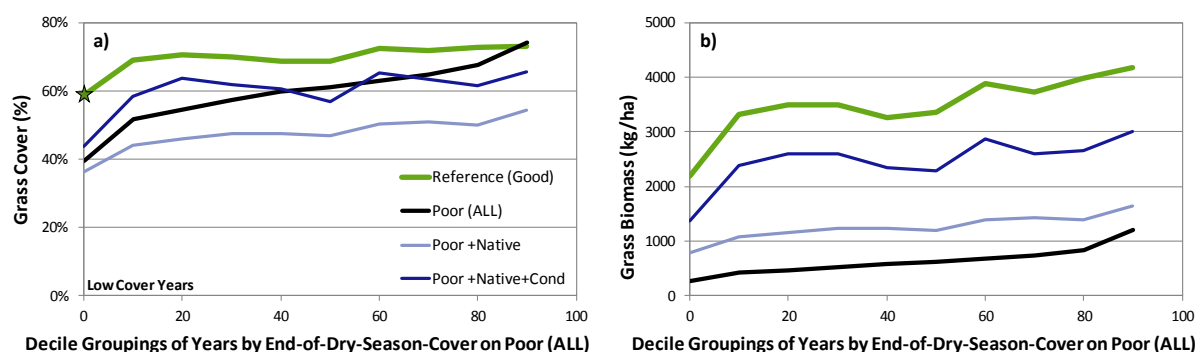


Figure 30. Effects of changes in land condition and pasture composition (representing long-term effects of improved management) on end of dry season (November); a) cover and b) biomass plotted for differing qualities of growth seasons (represented by decile groupings of the 125 years of simulation according to the level of cover in the Poor (ALL) scenario).

The sensitivity of cover to recent grazing pressure and rainfall also means that cover and cover deficit in any one year are only weakly determined by, and are not appropriate indicators of, land condition. The effects of management on land condition must be assessed using long-term cover; for example in Section 3 we saw that differences in land condition between focus properties were predicted well by mean cover over 25 years, but cover deficit could vary considerably over time. This highlights the need for improved frameworks for analyzing cover data that represent the cumulative effects of past management and changes in pasture composition on land condition.

6.3.3 Scenario modelling of pasture recovery

The results illustrate that exceeding the maximum stocking rates by even a small margin results in large changes in land condition (Figure 31a). Further, overoptimistic assumptions of recovery rates would result in overestimating the safe carrying capacity (Figure 31a). If recovery rate is slower then lower stocking rates are required to avoid land degradation in the long-term. This indicates model sensitivity to the long-term pasture response to grazing pressure, which is poorly constrained by observational data. Consequently, we do not report model predictions of liveweight gain for the focus properties, although it is noted that our simulations stocking all properties to achieve ~20% pasture utilization resulted in liveweight gain per ha on the High cover property about double that on the Low cover property. Therefore, better field data to quantify the rates at which pasture productivity degrades and recovers in response to climate and management is a clear priority to ensure land condition can be sustainably managed.

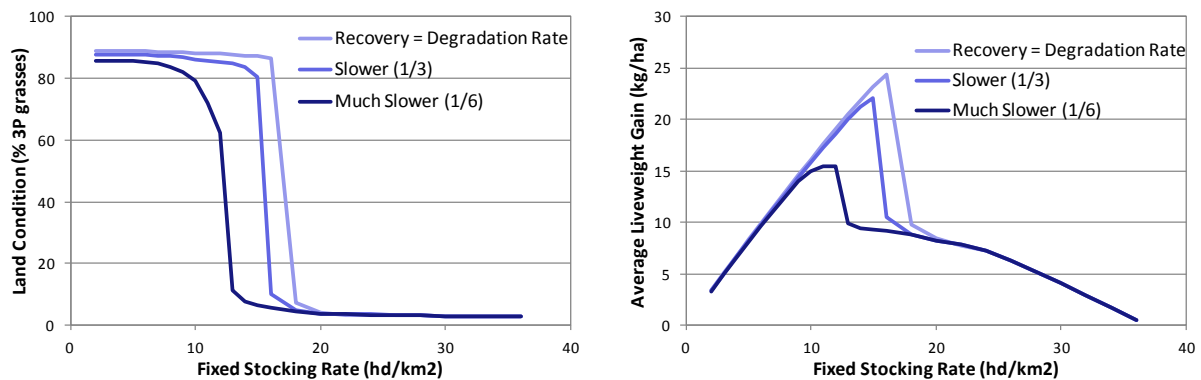


Figure 31. Implications of possibly overoptimistic expectations of land recovery rates for responses to stocking rate management. Safe long-term stocking rates occur before the point at which land condition and productivity decline. Data are averages over ~120-year simulations for a) land condition, and b) liveweight gain per unit area.

Consistent with the land condition outcome, the maximum sustainable productivity is also lower where recovery rates are slower. Long-term animal productivity (per unit area) initially increases as stocking rates increase, but then drop off substantially at stocking rates that lead to even modest degradation (Figure 31b). This identifies the priority to include a responsive element into management, to monitor any early signs of pasture degradation and reduce stock numbers accordingly.

In addition, slower recovery means that greater emphasis would need to be placed on conservative stocking during drought, because the of the reduced benefit of short-term gains of overstocking relative to greater long-term productivity losses, as land would take longer to recover. Further investigation is warranted into distinguishing between stocking strategy recommendations for land types covering a range of recovery rates, particularly in terms of the relative advantages of responsive stocking rate strategies and the different management criteria that would be used to adjust seasonal stock numbers in each situation.

7 Discussion

7.1 Reducing erosion generally requires lower stocking rates

The results clearly indicate that reducing stocking rates would increase vegetation cover and reduce hillslope erosion rates on most grazing properties in the soil type regions we studied. Relative to low-cover properties, medium cover properties had ~50% lower stocking rates and high cover properties ~75% lower rates. This resulted in high-cover properties having 5–10% higher ground cover over decades (~10–20% during drier years), and 30–60% lower hillslope erosion (Section 5.3). These estimates are consistent with previous estimates of 61–71% reductions in hillslope erosion for 20% increases in mean-annual cover (Thorburn and Wilkinson, 2013). This large potential for erosion reduction exists across about half of all properties in the regions studied, which were within our medium and low-cover focus categories (Table 5), or had declining cover deficit (Figure 19).

The highest rates of hillslope erosion rates occur at the lowest cover levels, rather than the highest rainfall. Therefore, it is critically important to maintain cover through droughts. Reducing grazing pressure commensurate with forage production is also pivotal to avoiding ongoing degradation of land condition (McKeon *et al.*, 1990).

We found that improving cover on C-condition land provided reductions in erosion that were similar to those resulting from improving cover on B-condition land. Consequently, grazing practice improvement to reduce hillslope erosion should be targeted equally at land in C and B-condition. The environmental drivers of erosion including rainfall, terrain and soil type are at least as important as current condition in determining the water quality effectiveness of reducing grazing pressure and increasing ground cover. However, due to the resolution of GCI ground cover data it did not completely identify the effect on hillslope sediment losses of improving cover on D-condition scalded areas. Scalded areas may be more prevalent in C-condition land, and both sediment tracing and runoff monitoring indicate they are dominant hillslope source areas where they exist.

Reductions in catchment fine sediment yield are likely to be somewhat smaller than the scenario reductions in gross hillslope erosion. The hillslope erosion reductions are a conservative estimate of the reductions in sediment loss from hillslopes to streams, because increased cover also reduces the efficiency of sediment delivery to streams. However, gully and streambank erosion contribute 50–80% of catchment fine sediment yield (Wilkinson *et al.*, 2013; Hancock *et al.*, 2014)., and property-scale increases in cover would likely result in reductions in gully and streambank erosion smaller in magnitude than hillslope erosion, provided that grazing pressure was controlled adjacent to these features (Thorburn and Wilkinson, 2013).

7.2 Grazing management is about more than just cover

We have shown that in the long term (decades) cover can be a reliable hindsight indication of land function and productivity. In this project, mean-annual dry-season GCI over 25 years clearly separated properties in terms of pasture composition, soil infiltration and stability (Section 3), nitrogen retention, and forage and protein productivity (Section 6). Similarly,

previous land condition assessments based on GCI have utilised all GCI data over 25 years (Karfs *et al.*, 2009).

In the short term, however, forage productivity is more dependent on forage biomass and composition, soil infiltration capacity and nitrogen pool, than on ground cover. Native perennial pastures are more productive in the long-term than temporally-variable exotic invasive species such as Indian Couch, which produces substantially lower biomass than native tussocks for the same cover (Figure 27). We found that beef production (kg/ha) declines sharply at stocking rates which cause pasture composition to degrade (Figure 31). The economic benefit of grazing within long-term carrying capacity to maintain the resource base is also supported by several case studies (Ash *et al.*, 1995; McIvor *et al.*, 1995a; Landsberg *et al.*, 1998; O'Reagain *et al.*, 2011; Star *et al.*, 2013). Gross margins tend to be less variable when grazing within the carrying capacity, due to minimal requirement for supplementary feeding (O'Reagain *et al.*, 2011).

A dominance of perennials in pasture composition is vital for increasing infiltration, and hence forage production, on degraded pastures dominated by Indian Couch. Indian Couch had low infiltration capacities at a range of cover levels, and this is consistent with 10 years of monitoring at Virginia Park (Bartley *et al.*, 2010a). In contrast, increasing cover can significantly reduce runoff volumes in perennial pastures (Owens *et al.*, 2003; Silburn *et al.*, 2011), due in part to the large basal area in pastures with native perennial tussock grasses (3P). Relative to perennial pastures, Indian Couch is hydrologically similar to annual species (Eldridge and Rotherton, 1992).

Areas under tree canopies are islands in woodland pastures, and help to maintain the resilience of landscape functions to grazing impact. Pasture composition is typically more diverse under woodland tree canopies than between canopies (Barnes *et al.*, 2009). Soil infiltration capacity can also be several times higher under tree canopies, reducing runoff at landscape scale (Eldridge and Freudenberger, 2005; Ellis *et al.*, 2006).

Sufficient forage biomass is also required before fire can be used as a management tool (Landsberg *et al.*, 1998), and given that some native pasture species depend on fire for higher germination rates (e.g., Mott, 1978), this is an additional reason for maintaining high forage biomass levels.

7.3 A cycle of recovery in productivity and function

About half of all grazing properties we studied would accrue long-term benefits in productivity and soil stability from reducing stocking rates, and the project has revealed much about the cycle of recovery required to achieve them. Relative to high-cover properties, forage productivity on low and medium-cover properties was more constrained by soil moisture and nitrogen availability. Forage biomass and basal area associated with a dominance of 3P pasture species, are key determinants of hydrologic function in terms of reducing soil movement and runoff. Therefore, rebuilding pasture productivity and soil stability requires recovery of 3P biomass, nitrogen retention, and soil infiltration capacity.

Changes in pasture cover precede changes in land condition, with changes in cover occurring much more readily and rapidly than functional changes in condition (Searle *et al.*, 2009; Bartley *et al.*, 2010a; Stokes and Wilkinson, 2013). A short-term increase in cover therefore indicates that an improvement in management or increase in rainfall has occurred, but the *potential* for future improvements in land condition will be realised only *if* improvements in cover and associated biomass are maintained over the longer term. There is a danger that assessing cover alone can lead to over optimistic expectations of the rates at which pastures recover from past over-grazing. In the long-term, the recovery cycle results in progressive improvements in hydrologic function and land condition (productivity), leading to higher long-term profitability and carrying capacity (Figure 32).

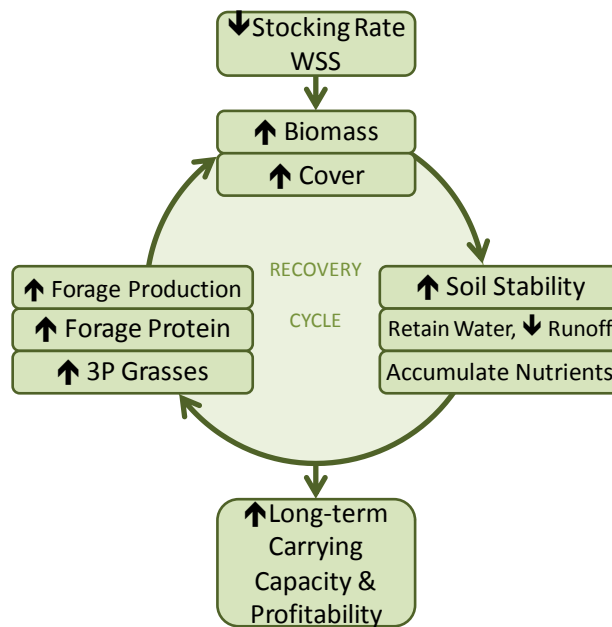


Figure 32. Progressive self-reinforcing cycle of pasture regeneration, after stocking rates are reduced and wet-season spelling (WSS) are introduced. Improvements in cover and biomass occur first, well ahead of functional improvements in land condition, which progressively recovers as higher cover levels are maintained over the longer term.

The above cycle of recovery can be structured into a transition hierarchy of the processes involved in degradation and recovery of each ABCD class of land condition (Chilcott *et al.*, 2003) (Table 10). Because transitions between A and B condition involve only small changes in pasture composition, changes in cover provide better indication of these transitions than between other classes. For areas in D condition, initiating recovery may require more than changes in grazing management alone, to address severe woody weed infestation for example.

Table 10. A transition hierarchy summarizing degradation and recovery transitions between 'ABCD' land condition classes, and their implications for interpreting changes in grass cover.

TRANSITION	DEGRADATION PROCESSES	RECOVERY PROCESSES
A ↔ B	Short-term loss of cover. Some decline in pasture productivity.	Reduction in utilization to restore plant vigour and cover.
B ↔ C	Longer-term periods of low cover prevent landscapes from retaining nutrients, leading to a progressive decline in soil nitrogen (and carbon). Annuals increase at expense of 3P grasses.	Mid-term changes in stocking rate to restore cover. High cover levels by themselves do not signify recovery, but need to be maintained for prolonged periods, reducing landscape leakiness and allowing soil nutrient and carbon to slowly accumulate to their former productive state. Pasture composition recovers with increase in 3P grasses.
C ↔ D	Protracted and/or severe loss of cover leads to loss of physical soil. Low levels of plant available nitrogen and water limit productivity and the ability of grasses to form substantive protective cover, even during wet periods.	Slow to recover, particularly in landscapes with naturally shallow and/or infertile topsoils. More extreme interventions may be required to kick-start regenerative processes to rebuild and retain nutrient pools and soil.

The focus of grazing management efforts for pasture recovery is often on restoring C condition land to B condition, because this is understood to be where the greatest environmental and productivity gains are usually gained per unit of effort (Stokes *et al.*, 2012; Hunt *et al.*, 2013). However, our cover-change scenarios have shown that improving cover on B-condition land results in comparable t ha⁻¹ reductions in hillslope erosion rate (Section 5.3). In either case, recovery involves not only restoring cover, but also restoring and maintaining perennial tussock grasses and rebuilding stores of plant available nitrogen and soil moisture holding capacity.

As well as increasing productivity, increasing infiltration capacity over large areas should reduce river sediment loads in the long term, by reducing runoff volumes. Channel erosion from gullies and streambanks is a larger sediment source than hillslope erosion in many areas, and these processes are driven by runoff volumes more than by direct rainsplash. Therefore, increasing the perennial composition of degraded pastures is a key objective of improving grazing management for reducing river sediment loads.

7.4 Timescales and economics of practice change

Rates of recovery depend on the starting point, soil fertility and climate. In low-cover pastures with intact native perennial pastures and moderate soil fertility, recovery of cover, biomass, soil stability and soil infiltration capacity can occur within several years if climatic

conditions are favourable (Connolly *et al.*, 1997). On the other hand, where pasture composition is degraded and fertility is lower, recovery can require several decades of low forage utilisation. For degraded pastures on Chromosol soils, reducing forage utilisation resulted in cover and soil stability improving markedly within a decade, but only partial recovery of 3P grasses (from 5–10% to 20–25% of forage biomass), and negligible change in runoff (Bartley *et al.*, 2010a), or soil infiltration capacity (Figure 11). It appears that the 3P composition of pasture, the nitrogen pool and soil infiltration capacity at this site will continue to improve over coming decades if conservative management is maintained. This will have ongoing benefits in terms of further reductions in runoff and erosion.

Again it is stressed that responses are not always immediate, and even negative responses can occur in the early years before vegetation responses are complete (Eldridge and Robson, 1997). Conversely, on historically low-cover properties where continuous grazing at high stocking rates is ongoing, soil infiltration capacity continues to decline, and improving forage management will be required to avoid further degradation.

Both a field study and modelling have identified that short-term economics of reducing stocking rate are linked with climate cycles, and payback times are generally 7–10 years (Landsberg *et al.*, 1998; O'Reagain *et al.*, 2011). Knowing the correct recovery rates of forage productivity is essential for understanding the production risks of overstocking. Where pastures recover more slowly the consequences of incorrect stocking rate decisions will be more severe and enduring, meaning that more conservative decisions are appropriate. It is important to note that the same models and approach as used in our simulations have played a large part in setting recommended safe stocking rates and evaluating grazing management options in GBR rangelands.

Pasture recovery rates affect graziers attitudes to improving land management practices. While most graziers in the study region aspire to improve land condition, there is a strong reluctance to take the measures necessary to do so (Webb and Stokes, 2012). Much of this relates to the short-term loss of income while stocking rates are reduced and land condition recovers, before longer term economic and environmental benefits are realized (Landsberg *et al.*, 1998; O'Reagain *et al.*, 2011). The longer pastures take to recover, and the longer the period of reduced income, the higher the impediment is likely to be for managers to commit to improving land condition. However, slower recovery rates can also result in unexpected degradation events, affecting ongoing profitability under current management.

Finally, from the perspective of the public investor in practice change, there are credibility risks if claims of early success, based on short-term increases in cover, are exaggerated, and fall short of producing the anticipated functional outcomes in productivity and erosion over the longer term.

7.5 Monitoring recovery in productivity and function

We have shown that cover deficit in dry years (Bastin *et al.*, 2012) can provide a useful measure of short-term (seasons to years) grazing impact across regions, by property (Table 5). Cover deficit has the advantage of isolating the grazing impact on cover from the effect of spatial variations in rainfall. Timeliness of cover deficit data availability to land holders would

be critical for detecting cover decline, to enable management responses ahead of pasture degradation occurring.

Trajectories of change in grazing impact between droughts can also be assessed with cover deficit by comparing with the same location or comparable pasture types in previous droughts. Benchmarking changes in cover deficit relative to properties of comparable cover deficit in previous droughts can help to correct for the influence of land condition on cover deficit (Figure 19). Large reductions in stocking rates (~50%) may be required to cause significant ongoing improvement in cover deficit.

Field observations of cover can be used to estimate pasture biomass and seasonal forage production for feed budgeting and planning seasonal stocking rates only if those observations are locally calibrated to the pasture type (which may explain why forage budgeting is underutilized in practice). Field monitoring is also required, to quantify the grazing impact on pasture productivity and hydrologic function on different land types. We have demonstrated that both LFA and patchkey provide useful measures of land condition that are correlated with soil infiltration capacity, soil erosion, forage nitrogen pool, pasture productivity, and pasture robustness in extended dry periods. We recommend these techniques for monitoring responses to practice change in GBR regions. Potentially GCI-based methods such as cover deficit can be calibrated against field observations, so that in future, changes in function or condition can be inferred without field data (or with less of it).

7.6 Outcomes for industry

Many of the results and findings from this project were packaged into a factsheet to support discussions between graziers and extension officers about improving grazing practices (Appendix 3). This factsheet was circulated to NQ Dry Tropics, Fitzroy Basin Association and Meat & Livestock Australia, and is available for download: www.reefrescueresearch.com.au.

More conservative forage management is the key recommendation from this project, for most properties. None of our high, medium or low-cover focus properties reported using quantitative approaches to forage budgeting and setting or adjusting stocking rates, although the high-cover property managers generally understood the importance of careful forage management. We recommend that simple and practical tools and communication strategies continue to be developed that assist graziers to set stocking rates corresponding to sustainable levels of forage utilisation. These must be appropriate to the climates, productive capacity and current land condition of each grazing region. Grazer uptake would have considerable benefit for maintaining and improving land condition, and in many cases property profitability, in the long term.

From our limited discussions with graziers, we also conclude that supporting practice change benefits from, and may require, ongoing and focused extension activities. While most focus property graziers were genuinely interested in the research, research results do not trigger a commitment to alter grazing management on their own. Some points of feedback are paraphrased below to help illustrate the diverse considerations that have informed historical management of stocking rates:

Low cover properties: *“The shorter the grass the more productive it is for the animals... I would like to see a variety of more palatable species in the pasture... Reducing stocking rate would hurt me financially.”*

Medium cover properties: *“The grass is higher and more diverse at the back of the paddock [further from water]. We do not intend to reduce stocking rates, but to distribute grazing pressure more evenly using additional water points.”*

High cover properties: *“When the bank was here recently they asked why I didn’t increase my stock numbers. I told them that the high forage levels were what I wanted at this time [April 2013]. More grass means more infiltration, and I’ll be able to use it next year.... We will never forget how this property was in the 90’s, and we never want to go back there... We notice that with high forage levels it takes more rain before there is enough runoff to fill dams... Indian Couch (invasive exotic runner grass) is more evident in paddocks that are continually stocked.”*

The priorities for public investment in grazing practice change to improve water quality at regional scale needs to consider the contributions of and spatial variations in all erosion processes including hillslope, gully and streambank erosion. Forage management is one component of grazing practices which relate to those processes. A framework for integrating forage management into water quality improvement programs is proposed in Appendix 4.

8 Conclusions

From this research we draw conclusions regarding (i) site relationships between stocking rates, productivity and sediment loss, (ii) engaging the grazing industry and (iii) evaluating the effectiveness of practice change. Finally, we outline areas for further investigation:

Grazing practices in the Burdekin and northern Fitzroy basins can be modified in a targeted way to achieve substantial benefits for productivity and soil stability.

From this research we conclude that:

1. Maintaining ground cover during droughts is crucial to managing soil erosion, which is more sensitive to ground cover than rainfall.
2. Beef production (kg/ha) declines sharply at stocking rates which cause pasture composition to degrade, indicating that grazing within the long-term carrying capacity, and reducing stocking rates considering seasonal conditions and forage condition result in higher long term profits.
3. Instituting more conservative forage management on properties with lower levels of historical cover would initiate a recovery cycle that would improve pasture cover, biomass, composition and productivity, and reduce soil movement and runoff.
4. The magnitudes of reduction in stocking rates required to reliably maintain and improve land condition are of the order of 50% for properties with low or declining historical cover, and somewhat smaller reductions for medium cover properties.
5. In the long term, reductions of these magnitudes across land currently in either C-condition or B-condition should lead to cover levels 10–20% higher during drought years, and hillslope erosion rates that are 30–60% lower than current levels.
6. Time-scales of recovery in pasture productivity, and hydrological function including erosion, range between several years and several decades depending on the current land condition. Maintaining high levels of ground cover and forage biomass is a minimum requirement for recovery to continue.

This research can help inform extension and investment to achieve effective practice change within the grazing industry into the future.

We conclude that:

1. Ground cover remote sensing indicates considerable variation in stocking rates between individual properties, presenting an opportunity to target extension and investment to achieve more effective practice change.
2. The quantitative data from this research, on the benefits of maintaining good land condition for pasture productivity and soil stability, has been of considerable interest to some graziers and provides support to existing extension messages within the industry.
3. Supporting practice change involves ongoing and focused extension activities with individual landholders and across grazing regions.
4. Efforts to reduce sediment loss from grazing land appear to be constrained by a limited understanding of the linkages from forage utilisation to pasture composition and productivity and profitability, and by the very limited adoption of quantitative approaches to forage budgeting and stocking rate decision-making. Incorporating

project findings into industry communication strategies, and developing simple but quantitative grazier tools such as photo standards for forage budgeting, should assist improving uptake and understanding. Short-term economic costs of reducing herd numbers appear to play a major role in setting stocking rates.

A combination of field assessment and cover remote sensing has emerged which can assist monitoring and evaluation of practice changes into the future.

We conclude that:

1. Ground cover alone is not an accurate indicator of pasture productivity or hydrologic function. Patchkey and Landscape Function Analysis are more reliable indicators because they quantify pasture biomass, composition, basal area and soil surface condition, which are required for retaining soil, nutrients and rainfall onsite to support plant growth. For example, perennial tussock grasses with large basal area are more productive than the same cover level of the Indian Couch runner grass (*Bothriochloa pertusa*).
2. Ground cover deficit (the difference between grazed and non-grazed cover) in dry years is more accurate than ground cover for assessing short-term grazing impact by property across regions, because it removes the effect of rainfall gradients on cover.
3. Changes in property cover deficit between droughts can indicate changes in grazing impact over time, resulting from stocking rates and rainfall, provided they are benchmarked against other properties with the same predominant soil type, and similar pasture composition, as indicated by cover deficits in past droughts.
4. It is likely that previous pasture growth modelling has over-estimated sustainable stocking rates particularly in lower-productivity land types. This is due to assumptions about the recovery rate of productivity following drought being poorly-constrained and over-optimistic, particularly in lower-productivity land types.

Future research should target remaining knowledge gaps related to grazing management that improves water quality.

Extend the cover deficit assessment to all rangeland grazing properties in GBR catchments

Cover deficit can potentially be used to help identify properties within each catchment which have large potential for improved forage management, and to evaluate the direction and magnitude of cover change on properties previously involved in extension and water quality improvement programs. Potentially, historical cover deficits could help to inform assessment of current grazing practices. The method could also be used to help evaluate the impact of Reef Rescue projects on property vegetation cover, and this would be best done in future years with rainfall of less than the 3rd decile (30th percentile).

Monitor the land condition responses to practice change

There have been many more studies of land degradation than recovery, yet the latter is our objective. Further long-term monitoring studies are required to understand the rates and magnitudes of recovery in pasture productivity, runoff, nutrient availability and soil movement for a range of land types. Within this, quantitative understanding is required of the link between land condition and runoff, given that runoff drives gully and streambank erosion which make large contributions to sediment loads in many areas. Repeat monitoring

of soil moisture at multiple sites and at larger scale (e.g., multi-hectare areas using COSMOZ soil moisture probes, <http://www.ermt.csiro.au/html/cosmoz.html>) combined with physically-based water balance modelling, appear promising for this purpose. We also recommend that improved frameworks for analyzing cover data be developed to help refine land condition mapping into mapping pasture composition, which would help to assess impacts on hydrologic function, runoff and soil movement.

Map the cost-effectiveness of practice change investment

Industry desires continued improvement in the technical basis for investment priorities, in terms of the relative cost-effectiveness of funded practice changes to reduce river sediment loads. Some understanding of cost-effectiveness has been developed for forage management, showing an increased requirement for, and cost-effectiveness of, public investment on low-productivity land types (Star et al., 2013). More case studies of physical and economic outcomes of reduced utilisation should be compiled to strengthen the case that the productivity outcomes described here result in economic benefits.

A cost-effectiveness framework is required that extends to remediation of gully erosion features, and riparian management. Cost-effectiveness will also be improved by considering (i) the spatial patterns in environmental drivers of erosion such as soil type, terrain and climate, (ii) where is it cheapest to intervene, and (iii) willingness of land holders to make effective changes and to continue them after initial incentives cease.

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Appendix 1 - Publications

These publications are direct outputs of project RRRD032, or were contributed to by the team as part of the project:

- Bartley B, Wilkinson SN, Hawdon AA, Corfield JP, Abbott BN, Nelson B. 2011. From Beef to Reef: challenges and triumphs in reducing runoff and sediment yields at hillslope and watershed scales in Australian Rangelands. International Rangelands Congress.
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Appendix 2 - Implications of cover variation within GCI pixels on landscape erosion estimates

Aim

Previous research in this region has demonstrated that a disproportionate amount of erosion occurs on bare and low-cover areas (Bartley *et al.*, 2010a; Bartley *et al.*, 2010b; Silburn *et al.*, 2011). Erosion in areas with $\leq 10\%$ cover is approximately 100 times that under 95% ground cover (Rosewell, 1993). The level of ground cover and its arrangement within each pixel are important factors in estimating remotely-sensed ground-cover values. Smaller sized pixels are likely to better discriminate low levels of ground cover where that cover is fragmented or generally discontinuous. Here we compare GCI values for selected areas derived from 25m Landsat TM GCI product, and pan-sharpened 2m WorldView (WV) 2 imagery, to provide a test of the relative difference in long-term erosion between cover levels estimated using Landsat GCI.

Methods

WV2 image acquisition and processing

WV2 imagery was acquired for parts of several properties in the 2012 dry season. The image areas on each property ranged 1,500–7,000 ha. Imagery comprised 2m multispectral bands (MSS; visible blue, green and red bands, and near infrared) and a 0.5m panchromatic (pan) band.

The Brovey transform was used to pan-sharpen the MSS bands effectively producing 0.5m MSS imagery. Most trees and shrubs, and associated shadow, were discriminated with an upper threshold on NDVI (a greenness index) and a lower limit on the summed visible-band spectral values. Woody canopies and shadow were excluded (masked) to leave bare ground and varying levels of ground cover. Combined thresholds on the visible-red band (band 3) and the PD54 index (Pickup *et al.* 1993) were then used to map areas estimated to have $\leq 10\%$ ground cover.

Where tile effects were evident within images mosaiced from multiple capture dates, colour balancing based on spectral values of common pixels in overlapping areas was used to radiometrically standardise the entire image area. This was followed by pan sharpening and image segmentation to mask woody canopies and associated shadow. Recent fire scars were manually digitised and removed with the final analysis area also confined to mapped chromosol soils.

Areas with $\leq 10\%$ cover were mapped with visible red-band values ≥ 178 (with the PD54 index providing no additional discrimination value) and ground cover (%) estimated as

$$141.67 - 0.60 * \text{band 3}$$

band 3 values > 238 were set to 0 and < 70 set to 100

Results

The areas of $\leq 10\%$ cover were reliably identified (e.g., Figure 33), and this was confirmed by field measurements where available.

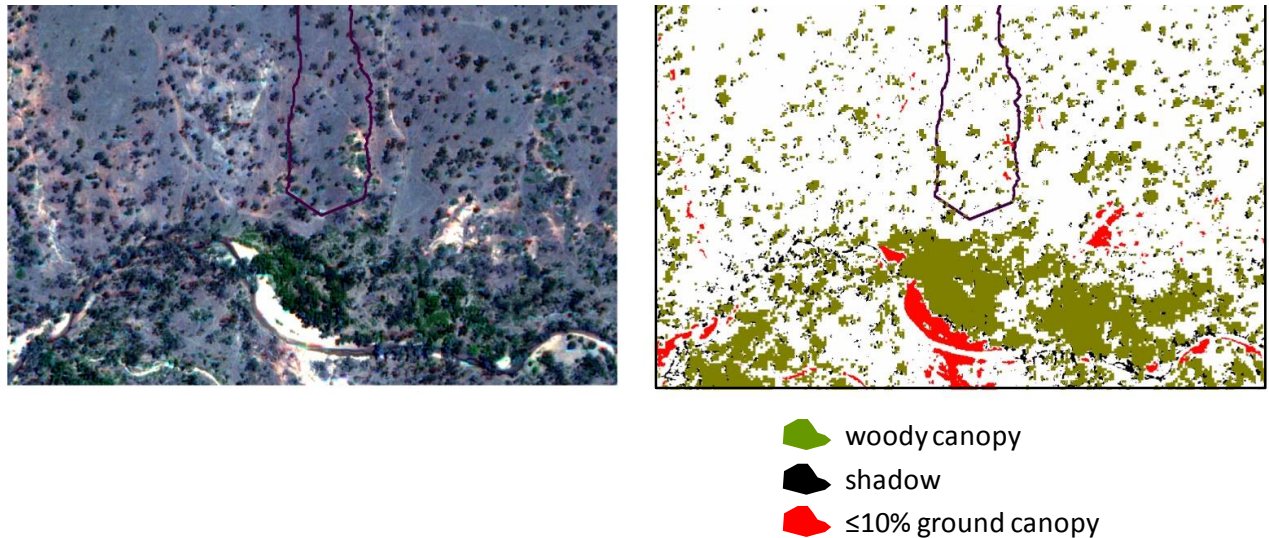


Figure 33. True-colour WV2 image surrounding and including the Flume 1 hillslope on Virginia Park (left) and classified woody canopies, associated shadow and ground cover $\leq 10\%$ (right). Image extent is 500m square (25 ha).

The GCI imagery under-predicted the proportion of area with $\leq 10\%$ ground cover at all sites by generally 1–2 orders of magnitude (Figure 34). Within the area identified by WV2 as having $\leq 10\%$ ground cover, the GCI imagery estimated cover of 90% cover in 2010, and $>40\%$ cover even in the dry 2003 year. Consequently, hillslope erosion estimates based on GCI cover data will tend to under-estimate hillslope erosion rates at all sites, by the greatest margin at low-cover sites.

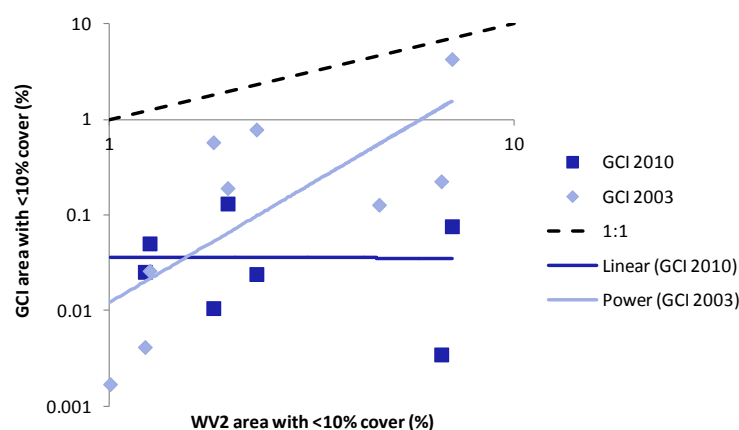


Figure 34. Mean GCI, where $\leq 10\%$, in 2003 (open symbols and dashed line) and 2010 (closed symbols and solid line) for areas of WV2 imagery estimated to have $\leq 10\%$ ground cover in 2012.

The resolution of GCI imagery is an important cause of over-estimation of cover. Approximately 50–90% of all WV2 bare patches across the different chromosol properties /

cover sectors were $\leq 4 \text{ m}^2$, and more than 95% of all patches were smaller than one Landsat TM pixel at many sites, especially low-cover sites (Table 11). Most of the largest patches ($> 6.25 \text{ ha}$, equivalent to ten or more TM pixels) were associated with sandy creek beds and thus not significant in terms of erosion.

Table 11. Frequency (%) of size classes for patches with $\leq 10\%$ ground cover on low cover and high cover sites. Patches were formed by aggregating neighbouring WV2 pixels. The maximum patch size on each property is also listed.

Patch size (m^2)	Corresponding number of Landsat TM pixels	Low-cover chromosol property	TFTA high-cover sector
≤ 4		88.02	52.32
5 to 10		6.74	16.84
11 to 100		4.61	28.47
101 to 625	≤ 1	0.52	2.13
626 to 1250	2	0.05	0.16
1251 to 1875	3	0.02	0.03
1876 to 2500	4	0.01	0.03
> 2500	> 4	0.02	0.01
Maximum patch size (ha)		7.84	2.26
Corresponding number of Landsat TM pixels		125	36

Appendix 3 - Grazing industry factsheet

The factsheet overleaf packages the material from Sections 3 and Section 6 to support discussions between graziers and extension officers about improving grazing practices. This factsheet is available for download from www.reefrescueresearch.com.au.



RRRD032 Land condition outcomes from grazing land management

CSIRO and DAFF have been running a collaborative study with graziers to look at the effect of historical cattle stocking rates on ground cover, pasture productivity and erosion. Graziers participating in the study provided information on past and present management practices and land condition monitoring. We used this information to identify stocking rates and strategies that lead to higher productivity and lower erosion rates in the long term.

We used 25 years of satellite imagery processed through VegMachine™ software to select focus properties with historically high, medium and low ground cover levels.

Pasture cover at all properties was high during wetter times. The effect of management practices and land condition became obvious during drought periods, when cover level declined depending on persistence of perennial grasses including 3P (perennial, productive and palatable) species (Fig. 1).

• Dark cracking clay soils (Vertisols)

We found that lighter stocking rates generally result in higher cover levels and heavier stocking rates have lower cover levels (Figure 2). Higher cover levels also supported higher pasture growth, and these findings were consistent across soil types. Importantly, high cover levels also retained about double the amount of nitrogen available for plant growth, producing more protein for livestock consumption (Figure 3).



Figure 1. Annual rainfall and dry season ground cover index for the three Red girdle focus properties.

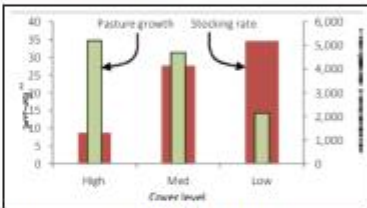


Figure 2. Lower animal equivalent stocking rate (AE), and higher pasture production, at higher cover levels, on Red girdle soils.

The project studied cover levels across three soil types common in the Fitzroy & Burdekin catchments:

- Red girdle soils (Chromosols)
- Grey/yellow duplex soils (Sodosols or 'spewy soils')

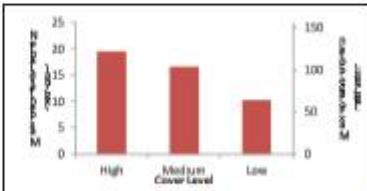


Figure 3. Higher whole-pasture Nitrogen and protein content at higher cover levels, from exclosures on Red girdle soils, re-clipped at the end of the growth season in April 2012.





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Field surveys at representative sites on the properties showed that long-term vegetation cover was an indicator of land condition and the abundance of 3P grasses. The capacity of soil to absorb water was higher at high cover levels, retaining more rainfall onsite to support pasture growth (Figure 4). Small plot measurements of soil erosion were up to 70% lower at high cover levels.

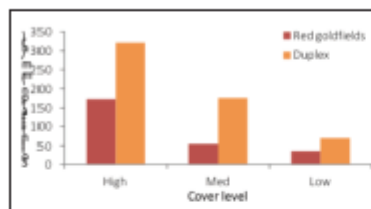


Figure 4. Higher soil infiltration rates at higher cover levels for Red goldfields and Duplex soil types.

Where does this lead us?

The good news is that cover, productivity and land condition can be improved. After reduced forage utilisation and wet season spelling practices commenced on Virginia Park in 2002, 3P grasses increased, and suspended sediment and nutrient losses in runoff declined (Figure 5).

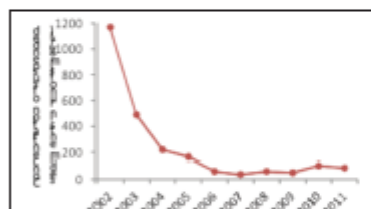


Figure 5. Decline in suspended sediment concentration in hillside runoff on a Red goldfields soil at Virginia Park, following introduction of reduced forage utilisation and wet season spelling in 2002 (study supported by Meat and Livestock Australia).

While reducing herd size can have economic costs from changes in turn-off over the short term (several years), the Wambiana grazing trial and other case studies show that moderate stocking within the long-term carrying capacity every year can more than double gross margin returns in the long term (within 10 years).

These gains result from higher live-weight gain and product quality, lower operating costs, and a more stable income through drought cycles (Figure 6). Pasture spelling and forage budgeting can also improve economic returns and land condition if applied correctly. Other grazing practices which reduce soil loss include moving grazing pressure away from scalds, gullies and frontage country, and remediating those areas to assist recovery.

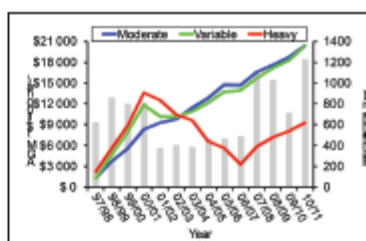


Figure 6. Accumulated gross margin (AGM) at the Wambiana grazing trial for moderate, variable and heavy stocking rates (study supported by Meat & Livestock Australia).

In summary, information from focus properties across a range of remote sensing cover levels has shown that management practices impact on land condition. Reducing stocking rates, particularly combined with wet season spelling, initiates a recovery cycle leading to long-term sustainability and profitability (Figure 7).

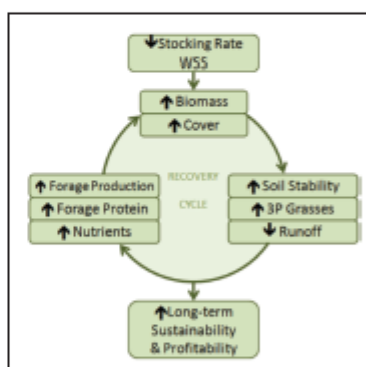


Figure 7. Improving land condition and profitability requires onsite retention of resources to support forage production.

Resources available

Good natural resource management is an asset for your business. Your local extension officer can assist you with courses on grazing management and forage budgeting, property planning and pasture cover data. Grants may be available through your Natural Resource Management group to assist with erosion problems and necessary infrastructure.

Contact

Scott Wilkinson, CSIRO, (02) 6246 5582
Karl McKelvie, DAFF Charles Towers, (07) 47 61 51 50

Appendix 4 - Priorities to reduce sediment delivery from grazing lands to the GBR lagoon

Public investment to improve agricultural practices and water quality in the GBR lagoon can be made more effective by prioritizing the spatial location and nature of practice changes. This prioritisation can be informed by quantitative data on grazing practices, erosion and sediment transport rates. Here we describe sequential stages to prioritize (1) between regions, (2) between management units, (3) between erosion processes, (4) between practices changes, and (5) the levels of investment that will achieve adoption of priority practices in priority areas:

Stage 1, Allocate investment across NRM regions:

At GBR scale, funding can be apportioned across NRM regions based on many considerations, including the proportional contribution to total pollutant (fine sediment) loading from all GBR rivers, capacity to achieve change, etc. This apportionment approach means that no region is excluded from funding, which is appropriate given that spatial variability in erosion means that all regions can be expected to have some highly-eroding areas.

Stage 2, Allocate investment across management units:

At the scale of NRM regions, there are strong spatial patterns in the intensity of pollutant contribution to the GBR coast due to variation in erosion rates and trapping in reservoirs and floodplains (McKergow *et al.*, 2005). Within each region, funding can be apportioned to each management unit (Dawson, Belyando, Mary, etc) based on their proportional contribution to regional pollutant loads to the GBR coast. This approach means that no management unit is automatically excluded from funding, which is appropriate given that spatial variability in erosion means that all units can be expected to have some highly-eroding areas. It must be ensured that the effects of reservoir trapping and floodplain deposition are accounted for to determine the management unit contribution to the coast, not just the loss from the downstream end of the management unit. P2R catchment modelling of pollutant loads is available in the MCAS tool (Barson *et al.*, 2013).

Stage 3, Prioritise property investments based on erosion source and erosion severity:

Of the fine sediment delivered to the coast 70–90% is derived from erosion of sub-surface soil features including rills, scalds, gullies and streambanks (Hughes *et al.*, 2009; Olley *et al.*, 2013; Wilkinson *et al.*, 2013a; Hancock *et al.*, 2014). Therefore, presence of these erosion processes is a primary consideration for targeting at property scale within management units.

Target properties within each management unit in descending order of erosion severity (based on the property average of each erosion process), in the following order of priority, using the latest datasets cited or related updates:

- a) Properties in descending order of gully areal density (or gully erosion probability) based on the best regional-scale mapping available (Hughes *et al.*, 2001; Trevithick *et al.*, 2008; Gilad *et al.*, 2012; Brooks *et al.*, 2013). Potentially within gullied areas, properties with poor cover deficit or higher soil erodability can be targeted. In areas

where it occurs, gully erosion is likely to be the largest and most concentrated of the sub-surface sediment sources.

- b) Properties with large extent of D-condition land, which has chronically low cover even in average years (Karfs *et al.*, 2009; Beutel *et al.*, 2013). Potentially within D-condition land, areas of higher soil erodability can be targeted.
- c) Properties with large ground cover deficit in past droughts. Cover deficit represents the difference between actual and nearby reference cover and large values indicate a high priority for reducing grazing pressure (Bastin *et al.*, 2012; Wilkinson *et al.*, 2014a). Spatial data are available from Queensland DSITIA for 1995 and 2004. The most reliable assessment of cover deficit is based on the average value over multiple droughts (back to 1987). Cover deficit (like cover) varies between soil types, so assessments are best made within areas having the same predominant soil order (Chromosols, Sodosols, etc) (Wilkinson *et al.*, 2014a). Trends in cover deficit can identify declining areas. Ground cover (Scarath *et al.*, 2006), or fractional cover, can be used directly within small areas, but is affected by rainfall gradients as well as grazing impacts (Wilkinson *et al.*, 2014a).
- d) Properties adjacent to streams with high bank erosion as mapped by P2R catchment modeling, or previous SedNet modelling (McKergow *et al.*, 2005). Streambank erosion supplies less sediment than gully or hillslope erosion but is more spatially concentrated in the landscape and so is easy to effectively target.

Stage 4: Design practices and infrastructure to address the targeted sources:

Reducing the erosion rate of sub-surface erosion features is effectively achieved by a combined approach of (i) reducing runoff into them from upslope areas, (ii) increasing their vegetation cover, and (iii) improving sediment trapping within the features (Shellberg and Brooks, 2013; Thorburn and Wilkinson, 2013; Wilkinson *et al.*, 2013b). Reducing runoff can be achieved by maintaining or achieving a high biomass of native perennial tussock pastures (Roth, 2004; Silburn *et al.*, 2011; Wilkinson *et al.*, 2014a).

On properties funded or targeted, through the above stages or otherwise, practice objectives are:

- Set stocking rates within the long term carrying capacity, and annually ensure <25% utilization of available forage by livestock; lower in less productive and fragile land types (Thorburn *et al.*, 2013b; Hunt *et al.*, 2014; Wilkinson *et al.*, 2014b). This also benefits long-term profitability (O'Reagain *et al.*, 2011).
- Reduce grazing pressure around erosion features by redistributing grazing pressure away using fencing and water points (Hunt *et al.*, 2007; Thorburn and Wilkinson, 2013).
- Revegetate erosion features, which can be enhanced by small 'stick-traps' to retain fine sediment, nutrients and seeds (Wilkinson *et al.*, 2013b).
- Promote native perennial pasture species through wet season spelling (Bartley *et al.*, 2010; Ash *et al.*, 2011).

The Reef Plan Water Quality Risk Framework for Grazing details actions to achieve these objectives. Further supporting information is available in recent reviews of grazing land management (Thorburn *et al.*, 2013a; Thorburn *et al.*, 2013b; Hunt *et al.*, 2014). Gully remediation has been recently reviewed (Shellberg and Brooks, 2013), and demonstrated (Wilkinson *et al.*, 2013b).

Stage 5: Vary public investment contribution to achieve adoption

Within priority properties, vary the maximum public investment based on:

- The effectiveness of the practice change being proposed considering the Reef Plan Water Quality Risk Framework for Grazing
- Capacity to pay; Higher productivity land (e.g., Dark cracking clay soils) may be able to co-invest more than lower productivity land (Star *et al.*, 2013).

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