## Abstract

Dissertation Title:	HUMAN-INDUCED VEGETATION DEGRADATION IN A SEMI-ARID RANGELAND		
	Hasan Jackson, Doctor of Philosophy, 2017		
Dissertation directed by:	Professor Stephen D. Prince, Department of Geographical Sciences		

Current assessments of anthropogenic land degradation and its impact on vegetation at regional scales are prone to large uncertainties due to the lack of an objective, transferable, and spatially and temporally explicit measure of land degradation. These uncertainties have resulted in contradictory estimates of degradation extent and severity and the role of human activities. The uncertainties limit the ability to assess the effects on the biophysical environment and effectiveness of past, current, and future policies of land use. The overall objective of the dissertation is to assess degradation in a semi-arid region at a regional scale (14 million hectares), where the process of anthropogenic land degradation is evident. Net primary productivity (NPP) is used as the primary indicator to measure degradation. It is hypothesized that land degradation resulting from human factors on the landscape irreversibly reduces NPP below the potential set by environmental conditions. It is also hypothesized that resulting reductions in NPP are distinguishable from natural, spatial and temporal, variability in NPP. The specific goals of the dissertation are to (1) identify the extent and severity of degradation using productivity as the primary surrogate, (2) compare the degradation of productivity to other known mechanisms of degradation, and (3) relate the expression of degradation to components of vegetation and varying environmental conditions. This dissertation employed the Local NPP Scaling (LNS) approach to identify patterns of anthropogenic degradation of NPP in the Burdekin Dry Tropics (BDT) region of Queensland, Australia from 2000 to 2013. The difference in units of mass of carbon and percentage loss were the measure of degradation. Degradation is then compared to non-green components of vegetation (e.g. wood, stems, leaf litter, dead biomass, etc.) to determine their relationship in space and time. Finally, the symptoms of degradation are then compared to land management patterns and the environmental variability (e.g. drought, non-drought conditions). Nearly 20% of the region was identified as degraded and another 7% had significant negative trends. The average annual reduction in NPP due to anthropogenic degradation was -17% of the non-degraded potential, although the severity of degradation varied substantially through the region. Non-green vegetation cover was strongly correlated with the inter-annual and intra-annual temporal trends of degradation. The dynamics of degradation in drought and non-drought years provided evidence of multiple stables states.

# HUMAN-INDUCED VEGETATION DEGRADATION IN A SEMI-ARID RANGELAND

by

Hasan Jackson

Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy 2017

Advisory Committee: Professor Stephen D. Prince, Chair Professor Matthew Hansen Research Professor César Izaurralde Research Professor Joseph Sexton Professor Joseph Sullivan © Copyright by Hasan Jackson 2017 Dedication

To my family, Banu Hasan of the Jackson tribe...

# Acknowledgements

I would like to thank my parents, Dr. Robert Jackson and Dr. Fatimah Jackson, for their unwavering support, encouragement, and guidance before and during my doctoral studies. I love you very much, now and forever.

I would like to thank Dr. Rishmawi, who provided early help with processing satellite data and broadening my understanding of vegetation dynamics.

I am also thankful to Drs. Hansen, Izaurralde, Sexton, and Sullivan for serving on my committee and providing helpful input and suggestions during individual and committee meetings over the course of my dissertation studies.

I am particularly grateful to my dissertation advisor, Dr. Stephen D. Prince, for his mentorship and support during my PhD studies. His knowledge, enthusiasm, curiosity attention to detail, and dedication provided an unmatched learning experience. His commitment to my doctoral studies, including weekly discussions, demonstrated his interest in my research.

# Table of Contents

Abstract	i
Dedication	ii
Acknowledgements	iii
Table of Contents	iv
List of Figures	vi
List of Tables	ix
Chapter 1 Introduction 1.1. Background 1.2. The nature and measurement of degradation 1.2.1. The nature of degradation 1.2.2. Measurement of degradation 1.4. Study Area 1.4. Research Goals 1.5. Research Strategy	1 3 5 15 18 20
1.6. Outline of Dissertation Chapter 2 Degradation of Net Primary Production	21 24
<ul> <li>2.1. Introduction</li> <li>2.2. Materials and Methods</li></ul>	24 26
2.2.1 Study area 2.2.1 Land capability classification 2.2.2. Measurement of NPP using satellite data	20 26 30
<ul> <li>2.2.3. Local net primary production scaling (LNS)</li> <li>2.3. Results</li> <li>2.3.1. UMDLCC</li> </ul>	31 <b>32</b> 32
<ul> <li>2.3.2. LNS</li> <li>2.3.3. Spatial variation in LNS</li> <li>2.3.4. Inter-annual trends in LNS</li> </ul>	35 37 39
<ul> <li>2.3.5. Comparison of LNS and environmental characteristics</li> <li>2.4. Discussion</li></ul>	41 <b>42</b> 42
Chapter 3 Degradation of Non-Photosynthetic Vegetation in a Semi-Arid Rangela 3.1. Introduction	45 nd . 48 48
3.2.1. Study area	<b>52</b> 52
<ul><li>3.2.2. Fractional Cover</li><li>3.2.2. Local Scaling of Components of Fractional Cover</li><li>3.3. Results</li></ul>	54 55 <b>58</b>
3.3.1. Comparison of Condition Metrics	58

3.3.2. Scaled Components of Fractional cover and Scaled NPP	59
3.3.3. Relationships between Components of Fractional Cover and Degradation	66
3.3.4. Inter-Annual Trends in Scaled Components of Fractional Cover	69
3.4. Discussion	71
3.4.1. Relationship between Components of Fractional Cover and NPP	71
3.4.2. Degradation and Components of Fractional Cover in the BDT	73
3.4.3. Interpretations of Non-photosynthetic vegetation	76
3.5. Conclusions	77
Chapter 4 Degradation: combined remote sensing and numerical simulation	80
4.1. Introduction	80
4.2. Methods	84
4.2.1. Study area	84
4.2.2. AussieGRASS Environmental Calculator	86
4.2.3. Degradation condition	87
4.3. Results	88
4.3.1. Comparison of simulated land surface properties with satellite-derived NPP	88
4.3.2. Comparison of model and remote sensing measurements of pasture condition	88
4.3.3. Comparison of intra-annual time-series for non-degraded and degraded condition	ons
in drought and non-drought years	92
4.3.4. Inter-annual variation	97
4.4. Discussion	102
4.4.1. Modeled simulations of biomass and its potential	. 102
4.4.2. Relating degradation to simulations of biomass and land surface properties	. 106
4.4.3. Potential improvements to AussieGRASS	. 111
4.5. Conclusions	112
Chapter 5 Synthesis, discussion and significance	.114
5.1. Context	114
5.2. Findings	115
5.3. Recapitulation of research questions	118
5.4. Anthropogenic and environmental degradation	119
5.5. Dimensions of degradation	122
5.6. Regional scale monitoring of degradation	123
5.7. Relevance to climate studies, global carbon budget and food security	124
5.8. Future research	125
5.8.1. Longer-term monitoring of land degradation	. 126
5.8.2. Improving the RESTREND procedure	. 128
5.8.3. Examination of human factors contributing to reductions in NPP	. 130
Glossary of Terms and Acronyms	. 132
Bibliography	.134

# List of Figures

Figure 1.1 Land-cover conditions in the Burdekin Dry Tropics region of Queensland, Australia (images adapted from Karfs et al.[1]). The Grazing Land Condition Framework for 'Goldfields Country on red soils' uses a land condition ranking system; (a) Very Good, (b) Good, (c) Poor, (d) Degraded. Factors used in visual evaluation include grazing pressure, erosion features, deposited materials, pasture density, ground cover, surface Figure 1.2 Illustrative figure of theoretical relationship between CAI (y-axis) and NDVI (x-axis) for 3 components of vegetation cover: Photosynthetic - Green; Non-Figure 1.3 Location of the Burdekin Dry Tropics (BDT, in red in first image) region in the State of Queensland, Australia, the six major river basins, and major roads and towns. Figure 1.4 Rainfall variation in the Burdekin Dry Tropics region in Queensland, Australia. Note: Rainfall from during drought years (i.e. 2004 to 2007) and during nondrought years (i.e. 2008 to 2011) were investigated (symbolized with darkened bars). Figure 1.5 Simplified schematic of research plan. Research objectives O1, O2, & O3 are addressed in Question 1; objectives O4 & O5 in Question 2, and objectives O6 & O7 in Figure 2.1 Location of the Burdekin Dry Tropics (BDT) region in the State of Figure 2.2 Annual average rainfall in BDT for 2000-2013. The dashed line is the 14-year Figure 2.3 Example of the use of the frequency distribution of NPP of pixels in a single LCC to calculate LNS values. The vertical line denotes the reference NPP at the 85 percentiles of the distribution. The abscissa is labelled in LNS, NPP, and percent LNS Figure 2.4 Mean square variance in reference NPP (MgC m-2 year-1) for UMDLCC and GLMLCC in relation to rainfall; (a) 'within-LCC' and (b) 'between-LCC' with best-fit Figure 2.5 LNS in BDT (a) & enlargements of the areas indicated in (a): (b) high/low LNS on either side of a station boundary; (c) variation within a single station showing gradients from low to high; (d) low LNS in eroded drainage area; (e) hillslope erosion resulting in bare surface with little to no vegetation cover; (f) area of tree removal with visible erosion and reduced cover. Black lines are the boundaries of river basins and red Figure 2.6 Time-series of maps of the Burdekin Dry Tropics from 2000-2013 showing (a) annual LNS percent values from 2000 to 2013 and (b) inter-annual trends in LNS Figure 2.7 Similarities between (a) annual hillslope erosion, (b) gully density, (c) rainfall erosivity, and (d) sediment load and percentage LNS as indicated by fuzzy numeric 

Figure 3.1 Location of the Burdekin Dry Tropics (BDT) region in the State of Queensland, Australia, the six major river basins (a) and five locations (b-f) identified as Figure 3.2 Conceptual relationship between components of fractional cover; Photosynthetic Vegetation (PV), Non-Photosynthetic Vegetation (NPV), and Bare Soil (BS) cover along CAI (y) and NDVI (x) axes. Adapted from Guerschman et al. [2]. .... 53 Figure 3.3 Comparison of the individual scaled components of fractional cover averaged from 2000 to 2013 (a) for the entire BDT from Nov to Apr showing, scaled photosynthetic vegetation (PV), scaled non-photosynthetic vegetation (NPV), scaled bare soil (BS) cover, a composite of scaled fractional cover components, scaled NPP, and Karfs et al. [28]'s ABCD land condition assessment from with (b) fine scale comparisons of the five locations shown in (a) and a true color composite of Landsat imagery. Grey Figure 3.4 The percentage of degraded pixels across a gradient of low-to-high scaled components of fractional cover: scaled photosynthetic vegetation (scaled PV), scaled non-photosynthetic vegetation (scaled NPV), and scaled bare soil (scaled BS) cover. ... 65 Figure 3.5 Comparison of inter-annual trends of individual scaled components of fractional cover and scaled NPP from 2000 to 2013 (a) for the entire BDT from Nov to Apr showing, scaled photosynthetic vegetation (PV), scaled non-photosynthetic vegetation (NPV), scaled bare soil (BS) cover, scaled NPP with fine scale comparisons of the five locations shown in (a) and a true color composite of Landsat imagery. Grey lines Figure 3.6 Plot displays the relationship between the inter-annual slope of scaled fractional cover and the proportion of significant, negative trends of scaled NPP, for each component of fractional cover: photosynthetic vegetation (PV), non-photosynthetic Figure 4.1 Rainfall variation in the Burdekin Dry Tropics region in Queensland, Australia. Note: Rainfall from both drought years (i.e. 2004 to 2007) and non-drought years (i.e. 2008 to 2011) was investigated (symbolized with colored bars). Dashed line Figure 4.2 The Spyglass and Lucky Break properties (i.e. grazing 'paddocks') that Figure 4.3 Flow chart of AussieGRASS Environmental Calculator showing the outputs used in this study (green filled boxes) and the components calculated (orange). Figure Figure 4.4 Maps of average LNS, peak of season pasture growth, total biomass, and percent dead biomass for drought (2004-2007) and non-drought (2008-2011) years. Note Figure 4.5 Comparison of monthly simulated land surface properties: Pasture Growth (kg ha-1 mo-1), Total Biomass (kg ha-1), Dead Biomass (kg ha-1), and Green Biomass (kg ha-1), showing the average of four drought years (2004-2007) and four non-drought years (2008-2011), for non-degraded (a, c) and degraded conditions (b, d) in the Spyglass Research Facility. Error bars show 1 standard deviation. The "degraded" and "nondegraded" condition was determined by the LNS value. Note the differences in vertical 

Figure 4.6 Comparison of simulated land surface properties: Percent Dead Biomass (A), Grassfire Risk (B), and Run-off (C) partitioned by non-degraded and degraded conditions for drought (2004-2007) and non-drought (2008-2011) years. Error bars are one standard Figure 4.7 Scatterplots comparing averages of monthly simulated land surface properties in non-degraded and degraded conditions in drought and non-drought years: growth (A & B), cumulative growth (C & D), total biomass (E & F), green biomass (G & H), dead biomass (I & J), percent dead (K & L), grassfire risk (M & N), and run-off (O & P). Note the differences in axes between each simulation of biomass accumulation. Continued on Figure 5.1 Time-series of inter-annual residual trends in deviations of normalized difference vegetation index (NDVI) from the expected values indicated by annual rainfall at single pixel in Brigalow gidgee scrubs land cover type (Lat: 146.88E, Long: -21.95N) in the Burdekin Dry Tropics region, Queensland, Australia: (a) Linear regression fitted to time-series; (b) Piecewise (segmented) regression fitted to identical times-series. The year 2002 is a significant breakpoint in (b). Note the difference in magnitude of the negative regression slope coefficients in (a) and (b). NDVI (1km<sup>2</sup>) derived from AVHRR sensor. Rainfall data obtained from Australian Bureau of Meteorology. ...... 127 Figure 5.2 Maps of the coefficient of determination (r2) for  $\Sigma$ NDVI and annual meteorological variables from Y2000-Y2012 in Burdekin Dry Tropics region, Queensland, Australia. Spatial variation in r2-value shows that several meteorological variables are correlated with NDVI, not precipitation alone as is often assumed.  $\Sigma$ NDVI derived from MOD13Q1. Meteorological data obtained from Australian Bureau of Meteorology......128

# List of Tables

Table 1.1 Regional survey of land management practices in the Burdekin Dry Tropics region in Y2001-2. Grazing land management was evaluated and assigned to one of four categories: Good management indicates sustainable land use. Poor management indicates sustainable land use. Poor management indicates land use likely to damage land condition and lead to degradation. Current land management suggests possibility for more sites to enter poor land condition. Modified from www.brs.gov.au/landuse. ...... 17 Table 2.1. Mean, standard deviation, and t-test of mean square variance of reference NPP (gC m<sup>-2</sup> year<sup>-1</sup>) for UMDLCC and GLMLCC, partitioned into between-LCC and within-Table 2.2. Average LNS (Mg C m<sup>-2</sup> year<sup>-1</sup>) in the Burdekin Dry Tropics (BDT) region for all six combinations of degraded and non-degraded LNS conditions and three interannual LNS trends – no trend, positive and negative trends. The percentage of BDT area Table 2.4. Degraded LNS class. Area, severity, and variation in LNS and LNS percent. sd Table 2.5. Non-degraded LNS class. Area, severity, and variation in LNS and LNS percent. Table 2.6. Negative trends in area, inter-annual rate, and severity of LNS for river Table 2.7. Positive trends in area, inter-annual rate, and severity of LNS for river basin of Table 2.8. VAST class comparison with inter-annual trends in LNS and average LNS. sd Table 3.1 Environmental factors used in creating land capability classes (LCCs) in the Table 3.2 Average of observed components of fractional cover, and their scaled counterparts, in the BDT for pixels assigned to either degraded or non-degraded NPP Table 3.3 Components of fractional cover along a gradient of average annual rainfall. sd Table 3.4 Regression of scaled net primary productivity (scaled NPP; from Jackson and Prince 2016, in press) with components of fractional cover; photosynthetic vegetation (PV) cover, non-photosynthetic vegetation (NPV) cover, and bare soil (BS) cover and their scaled counterparts. Significance of correlation coefficient (r): for n > 2000, r > 0.19Table 3.5 Comparison of kappa values for maps of seasonal components of fractional cover, seasonal NPP, scaled components of fractional cover, scaled NPP, and the Karfs et al. ([28]) ABCD condition in the Burdekin Dry Tropics. Comparisons were made with the fuzzy kappa statistic [150] applied to each pair of maps taken as a whole, hence the Table 3.6 Comparison of ABCD condition, from Karfs et al. [28], with scaled NPP and  Table 3.7 Slope and correlation coefficients and standard deviation of residuals from linear regression between each component of fractional cover; photosynthetic vegetation (PV) cover, non-photosynthetic vegetation (NPV) cover, and bare soil (BS) cover identified as degraded and non-degraded by scaled NPP. Scaled components of fractional cover are also presented. See Table 2 for the significance of correlation coefficients (r).67 Table 3.8 Comparison of kappa values for maps of inter-annual trends in scaled components of fractional cover and inter-annual trends in scaled NPP in the Burdekin Dry Tropics. Comparisons were made with the fuzzy kappa statistic [150] applied to each Table 3.9 Vegetation Assets, States and Transitions (VAST) classification comparison with inter-annual trends for scaled components of fractional cover. sd - standard deviation......73 Table 4.1 AussieGRASS Environmental Calculator biomass, productivity, fire risk and Table 4.2 Monthly simulated land surface properties with equations and descriptions. All simulations of biomass have identical units (kg/ha), spatial resolution (5x5km) prior to resampling to 250 x 250m, and were calculated as monthly averages of drought (2004-Table 4.3 Regression of simulated-January productivity (Pasture Growth) and biomass (Total Biomass and Percent Dead Biomass), with reference NPP for the average of four drought (2004-2007) and four non-drought (2008-2011) years on reference NPP. Significance of correlation coefficient (r): for n > 2000; r > 0.19 is significant at the  $p \le 1000$ Table 4.4 List of non-degraded and degraded simulated land surface properties regression slopes that were not significant for drought years, non-drought years and between drought and non-drought years. Note: regressions were performed on averaged monthly values during drought and non-drought years; all other regression slopes not included were significantly different ( $\alpha = 0.05$ ) within degraded and non-degraded slopes or the 

## Chapter 1 Introduction

#### 1.1. Background

Drylands, consisting of land areas in tropical and temperate regions where the mean annual precipitation is less than two thirds of potential evaporation (aridity index of less than 0.65), cover approximately 40% of terrestrial Earth with over 38% of the global population, including much of the world's most impoverished populations [3-5]. The poor economic state of many inhabitants of drylands only exacerbates local dependency on ecosystem services [6]. Poor land use management such as overgrazing and unmanaged fire have been reported in some drylands with far reaching effects.

Rangelands are defined in this dissertation as grazing land (both commercial and non-commercial) in dryland areas. Rangelands undergoing poor management resulting in land degradation may experience deleterious effects on the function of key biogeophysical processes [7]. These effects also disrupt several key landscape processes, causing physical and chemical changes in soil characteristics (e.g. soil texture), disruption of the water and energy balances, diminished production and vegetation cover (e.g. pasture and agricultural yield), reduced carbon sequestration, increase in woody species (including unpalatable shrubs), increase in unpalatable species, and decreases in surface litter ultimately inducing soil erosion [8-14]. In rangelands, each process is considered a symptom of land degradation.

Land degradation resulting from human factors, including poor land management, is not well understood, in part due to uncertainty in defining the term. Various definitions for land degradation have been put forth in specific regions (e.g. Australian drylands, [15,16] and globally [4,17-19]. Common among these definitions are the processes resulting in reduced biological productivity, caused by various factors including climatic

variations and human activities. In this study, productivity is interpreted as net vegetation production. Thus, land degradation as investigated in this study refers to the process by which less productive conditions emerge over several consecutive seasons due directly, or indirectly, to anthropogenic influence on the landscape.

An example of widespread land degradation can be seen in the drylands of the Australian continent. Distinct alterations in land cover due to land use change in Australia have characterized the continent since European settlement [20]. Livestock grazing is Australia's most extensive land use, occupying 58% of the continent (www.brs.gov.au/landuse). In many grazing areas, reports suggest land condition has become degraded, as indicated by reduced pasture productivity and land surface water, sediment, and nutrient loss [16,21-24] often flowing into coastal waters [25]. An example of the regional effects of degradation is in the Burdekin catchment in Queensland, Australia which is linked to the silting up and death of corals in the Great Barrier Reef lagoon. The Australian Government has allocated \$200 million (Australian dollars) through the Reef Rescue package to help rangeland managers improve grazing land management strategies that increase pasture cover and reduce the erosion (http://www.nrm.gov.au/funding/2008/reef-rescue.html). Yet this investment is based on an assumption that regional land management causes catchment degradation and large scale sediment transport, which has yet to be proved anywhere globally [26]. The causes of poor landscape condition in Australian rangelands are known in Great Barrier Reef catchments (e.g. the Burdekin catchment): overgrazing, unmanaged fire, drought, and conversion of feral land to agriculture [1,27-29].

Similar to the Burdekin catchment area, estimates of the global extent, areas relevant for assessments at continental levels, of degradation have varied significantly. Despite estimates suggesting 50% to upwards of 70% of rangelands exhibiting symptoms of degradation, many question methods that have been used to map dryland degradation [30]. Even regional scale, areas comprising several million square hectares, estimates of the extent of land degradation are subject to uncertainty from varying interpretations [31-34] and reinterpretations [35-37]. Only at the local scale, areas comprising less than 100 hectares, are the dynamics of land degradation reliably monitored, often with in-situ measurements, but the relevance of these studies to the regional scale is unknown and likely to be low. The true extent of regional degradation has eluded reliable measurement [32,38-40]. Uncertainties in spatial and temporal patterns of degradation at the regional scale continue to limit the ability to assess the effectiveness of past, current, and future policies of land use [41].

Despite the aforementioned limitations, monitoring of land degradation has still been carried out throughout the world using various techniques. These have been undertaken at a wide variety of scales, from global to regional to local (see Appendix 1), including North America [42], China [43], the Mediterranean/Middle East [44-46], African drylands [32,47,48], and Australia [39,49], among others. Wide-ranging evaluations of global land degradation have varied [30,50-54]; providing contradictory interpretations of degradation extent and severity and the role of human influence.

## 1.2. The nature and measurement of degradation 1.2.1. The nature of degradation

Irreversible land degradation is indicated by the inability of vegetation to respond to favorable weather as well as similar land subject to less intense land utilization for grazing and farming. The return of favorable weather, for example increased rainfall after

previously dry years, at degraded locations will distinguish those locations which have low productivity owing to unfavorable weather (e.g. drought) from those which have low productivity irrespective of changes in weather (degraded over the long term). Recent increases in rainfall in some drylands, especially in the African Sahel and parts of Australia, are helping to distinguish short-term fluctuations and long term degradation. Persistent reductions in productivity after degrading factors are statistically controlled (normalized) are characteristic of the irreversible nature of the type of land degradation that is given the term "desertification" [7,55].

Exploration of the primary environmental factors related to natural differences in vegetation production will identify how much natural variability in vegetation production can be attributed to environment. The approach of this dissertation will be to minimize variation which can be explained through natural phenomena (e.g. spatial variations in soil type, inter-annual variation in weather patterns). Residual variation in productivity may indicate the presence of anthropogenic influence on the landscape. The presence of reduced vegetation production – that is, production below the expected in the absence of human action thus not related to natural factors, along with documented land use history will help assess the role of non-natural factors in influencing distributions of vegetation production. Relating indicators of land management with differences in vegetation productions in production will give an indication of possible human activity related to reductions in productivity.

Anthropogenic degradation, the topic of this project, differs between land use type and intensity, such as livestock grazing and dryland farming. High land use intensity, for example overstocking on pasture, frequently cause soil compaction, removal of plant

cover; reducing satellite based measurements of NPP and changing species composition, sometimes to the extent of woody encroachment.

This dissertation aims to provide an indication of the natural and human factors related to reductions in vegetation productivity. Monitoring and mapping of land degradation is necessary to obtain estimates of the extent, severity, and possible contributing human factors related to human induced land degradation. Monitoring will also provide an indication of ongoing land degradation while mapping will provide an indication of past and present extent of land degradation.

Attempts have been made to monitor land degradation using vegetation characteristics; however, there are inadequacies in previous methods which limit objectivity, repeatability, and transferability of land assessments. The conflicting accounts of degradation extent further emphasize the need for effective monitoring of land degradation. Furthermore, the deleterious impacts associated with human-induced land degradation have the prospect for undermining efforts aimed at promoting favorable rangeland management. Monitoring of human induced land degradation, in both time and space, is necessary to improve understanding of the mechanisms resulting in unfavorable vegetation change and the associated effects on the biophyiscal realm. There remains an oppurtunity to improve regional monitoring of land degradation, within Australian drylands and throughout the world, using repeatable methods based upon quantitative measues of vegetation which emphasize objectivity.

## **1.2.2. Measurement of degradation**

## **1.2.2.1.** Spatial scale of vegetation monitoring

Monitoring of degradation is needed at regional scales ( $\geq 1$  million hectares) for

relevance in policy decisions that extend beyond the local scale of single grazing

enclosures. In fact, some have argued that long term degradation is only usefully monitored at regional scales [7,55]. Many current studies however are performed at local scales (e.g. sub-hectare). At the local scale, degradation mapping has been investigated at field and hillslope scales, at hectare and sub-hectare areas respectively, for example, in Australia (Figure 1.1; [22,28,56-59]). These assessment scales only capture local conditions of vegetation and land management and are often difficult to extrapolate to regional scales [27].



Figure 1.1 Land-cover conditions in the Burdekin Dry Tropics region of Queensland, Australia (images adapted from Karfs et al.[1]). The Grazing Land Condition Framework for 'Goldfields Country on red soils' uses a land condition ranking system; (a) Very Good, (b) Good, (c) Poor, (d) Degraded. Factors used in visual evaluation include grazing pressure, erosion features, deposited materials, pasture density, ground cover, surface litter, yield, basal area (live & dead).

## 1.2.2.2. Qualitative Vegetation monitoring

Qualitative (e.g. Figure 1.1; [1,16]) monitoring of land condition has drawbacks.

Much of the difficulty stems from varying interpretations of what constitutes poor land

condition (e.g. livestock production, crop yield, changes in biodiversity, woody plant encroachment, reduced forage palatability, increased susceptibility to erosion). Reynolds et al. (2007) presented an examination of the consequences of land degradation measured qualitatively in both anthropogenic and biophysical realms [60]. Underlying qualitative reporting and anecdotal accounts is inherent uncertainty associated with local monitoring techniques and the lack of uniformity in land assessment over large areas that are relevant to long term degradation. While local expertise is an invaluable component in vegetation assessment, without truly objective methods, assessments are susceptible to bias [27], and these monitoring efforts are difficult to replicate in other ecosystems.

#### **1.2.2.3.** Quantitative Indicators of vegetation condition

Difficulty in the regional quantification of productivity is a result of variable approaches of measurement [39,48,57,59,61-65]. Prince [7] hypothesizes that deleterious changes in vegetation structure, vegetation dynamics, species composition, and soil properties reduce observed vegetation production. Net primary productivity (NPP) is the accumulation of primary production after costs of plant respiration have been deducted through time. The Normalized Difference Vegetation Index (NDVI) has proved strongly correlated with NPP [66-69], particularly in semi-arid and arid regions [70-74]. Seasonally integrated NDVI ( $\Sigma$ NDVI), reduced primary productivity and reduced plant cover have been used as measureable symptoms of degradation in regional studies. Previous efforts assessing the character of variations in productivity have used NDVI as an objective indicator of vegetation dynamics in drylands [32,34,75-80].  $\Sigma$ NDVI derived from satellite remote sensing data will be used as a proxy for NPP in this study. Moreover, the proposed use of regional satellite remotely sensed datasets will allow for an objective measure of vegetation production independent of local experience or agroeconomic models. While evaluation of remotely sensed data products is often difficult at regional scales, it does provide a quantitative component previously missing.

While NPP is commonly used for studies of vegetation condition, there are other techniques that have been used to monitor vegetation. Sites with minimal grass cover compared with otherwise similar sites over several years may also indicate degradation; however, land cover types may vary in expected cover.

Ground cover, the vegetation (living and dead) that covers an otherwise exposed



soil surface [81], has a significant impact on the retention of soil carbon and the ability of vegetation to respond to rain after episodic drought [57,62]. Local measures of ground cover have been investigated in land condition studies, particularly in Australia, at local scales ( $\leq$  100 ha; [56,58,59,62,65,82-85]. In this study, changes in cover will provide a second, measureable, indicator of land degradation.

The presence of non-photosynthetic herbaceous vegetation, either as standing dead plant or detached plant litter, cover may indicate landscape resistance to erosion, changes in the surface water and energy balances, and changes to surface soil structure [16,86]. Dry surface litter is measurable in dry dead vegetation by remote sensing through the detection of cellulose and lignin. Cellulose has a distinct absorption spectrum of solar radiation at 2000nm, 2100nm, and 2200nm. The cellulose absorption index (CAI; [87-91]) discriminates dry litter from dry soil using this relationship.

The use of CAI has been limited by the lack of remotely sensed measurements in the appropriate short-wave infrared parts of the spectrum. Currently the data from only one satellite instrument is entirely suitable (ASTER), but it is very difficult to acquire the desired temporal and spatial coverage for this application. However, recent data sets which are correlated with the CAI have become available for the entire continent of Australia, and it is proposed in this dissertation to use this to aid discrimination of nonphotosynthetic vegetation from bare soil as an additional metric of land function. Recently, Guerschman et al. (2009) have made a surrogate index for CAI using MODIS surface reflectance data in different wavebands [2]. The ratio of MODIS bands SWIR3 and SWIR2 (2200nm and 1600nm, respectively) corresponded well to CAI calculated using hyper-spectral data [2]. Soils can be spectrally differentiated from vegetation by the relatively flat reflectance spectra in the SWIR region. Extensive field evaluation was performed in mixed tree-grass ecosystems throughout Australia, including much of the Queensland. The relationship between CAI and NDVI has been used to distinguish bare soil (low CAI, low NDVI), non-photosynthetic vegetation (high CAI, low NDVI), and photosynthetic vegetation (intermediate CAI, high NDVI) (Figure 1.2, [2]). This method may provide additional understanding of regional vegetation production in instances of degradation.

Production and productivity are closely related vegetation properties, and production has also been used as an indicator of degradation in drylands [48,49,92-95].

Productivity is defined as the rate at which carbon is sequestered and converted into plant material in each area (e.g. kg ha<sup>-1</sup> month<sup>-1</sup>), whereas production is the accumulation per area (e.g. kg ha<sup>-1</sup>) result of productivity. While below-ground production is an important component of the global carbon budget [8,14,96-104], it is difficult – often impossible, to measure using a non-destructive method (e.g. remote sensing). Additionally, fluctuations in above-ground production are the more readily observable vegetation dynamic and by far the biggest dependency to secondary production (e.g. livestock). In this dissertation, biomass refers to the above-ground production. This use of biomass differentiates it from NPP and allows for independent comparisons between vegetation properties.

The use of observations of productivity and production, remotely sensed or surveyed, are subject to scattered removal from herbivories or management. Mechanistic modeling of biomass, on the other hand, may provide a systematic relationship between productivity and production. A key difficulty in previous degradation assessments are the limits in knowledge regarding management practices [27]. The linkages between land condition and management is an ongoing investigation in Australian rangelands [65,93,95,105-108], resulting in the development of highly parameterized models [109,110]. In fact, few other models have ingested more management properties (e.g. stocking rate, stock type) than those operated in Australia. Monitoring land condition (via biomass) through the integration of both human and natural factors is essential for building a science for degradation in drylands [7,60,111].

## 1.2.2.4. Temporal scale of vegetation monitoring

A key difficulty in assessing land degradation is distinguishing anthropogenic degradation from natural variability in NPP caused by differences in weather. Insufficient consideration has been given to the temporal persistence of the land degradation. To

identify degraded regions, long term NPP data are needed. Field surveys carried out in one or a few years cannot detect temporally defined conditions such as persistent degradation or trends characteristic of land degradation. Short-term fluctuations in production may be caused by spatial variability in weather and are normally termed droughts. Long term trends in productivity, however, may represent other processes, possibly human in origin, influencing vegetation condition. Changes in patterns of land use and/or returns toward more favorable climate regimes may not result in the land regaining former productivity under degraded conditions [7].

The use of satellite derived NDVI data in the proposed study will allow for monitoring of vegetation production and identifying locations with low productivity over multiple seasons. Seasonally summed-NDVI (ΣNDVI), used as a proxy for NPP, is derived from satellite remote sensing data. Regionally relevant satellite data records, which are available in various forms, for up to 32 years, extend from the early 1980s (AHVRR 1km) and 2000s (MODIS 250m). MODIS sensors have proved an improvement to earlier sensor systems (e.g. AVHRR) in producing more reliable measurements of surface reflectance at finer spatial and temporal resolutions. MODIS NDVI data have shown better agreement with in-situ measurements of NDVI in drylands than AVHRR GIMMS NDVI [112].

#### **1.2.2.5. Establishment of reference locations**

Land degradation is a relative concept, defined through a comparative assessment between distinct states of the land [4]. Potential productivity refers to the productivity (i.e. an also production) of the land in the absence of human influence. Comparing degraded conditions with the potential productivity gives an indication of the severity of the degradation.

Estimation of potential NPP from undisturbed reference sites will be used for assessment of land degradation. Previous studies have quantified reductions in NPP through spatial comparison with reference locations using satellite data [48]. These techniques will be used in this study to estimate potential NPP at the regional scale using sites with high productivity. Reduced vegetation productivity will be measured by the difference between its observed NPP and the potential NPP in the absence of land management.

#### 1.2.2.6. Normalization of the environment

The natural environment may influence estimates of the extent and severity of land degradation. Differences in the environment may mask measureable patterns in NPP which result from biophysical differences not related to degradation, e.g. soil type, soil hydraulic properties, topography, and weather. For example, NPP at sites with significantly different rainfall regimes (e.g. differing seasonal accumulation or rain periodicity) will result in over-estimation of non-degraded NPP values. The interpretation of NPP loss would then reflect rainfall gradients rather than differences in land use intensity. This may lead to overestimation of land degradation extent and severity in areas only experiencing national gradients in rainfall.

Topographic features may also influence NPP. Differences in the intensity of solar radiation and availability of moisture (in both air and soil) for vegetation on north-facing slopes, as opposed to south-facing slopes, may alter productivity [citation]. Thus it may be expected that NPP will vary with aspect and slope degree. Even subtle changes in topography greatly influence microclimate and can promote or reduce productivity (e.g. hillslope erosion, [86]). Important differences in terrain have been neglected in current

studies of land degradation partly due to the limited availability of digital global datasets of topography at useful scales.

#### 1.2.2.7. Mapping of land degradation

The Local Net production Scaling (LNS) Procedure

An approach used for the mapping of past and present extents of land degradation is the Local Net production Scaling (LNS) method, which has been used in the African Sahel as well as in South Africa [47,64] and Zimbabwe [48]. LNS allows for the spatial representation and quantification of sites with consistently low productivity relative to sites with observed high productivity.

The benefit of the LNS technique is that it allows for the spatial comparison of deviations in observed NPP from the potential NPP in a diverse regional environment. The heart of the LNS method is the identification of pixels that are subject to identical biophysical conditions but which have lower NPP than pixels identified as at the potential for the environment. This is achieved by a detailed stratification using all available data on factors that may influence NPP, other than anthropogenic. The aim is to create strata in a way that maximizes internal homogeneity of the biophysical variables that control NPP in each one. Polygons of pixels belonging to each stratum may be disconnected from each other. These strata are referred to as land capability classes (LCCs).

Potential NPP is estimated using spatial comparison within a LCC. For each homogeneous LCC, the NPP of non-degraded sites is calculated as the mean for an upper percentile of the observations (generally 85%, but adjustable in specific applications after examination of the frequency distribution for each LCC). This removes the effects of spurious high NPP values that can result from inadequate stratification, for example

including a riparian area in dry grassland. This new, adjusted, maximum NPP (mNPP<sub>r</sub>) value is the estimate of the potential NPP (pNPP).

$$pNPP = mNPP_r, \quad r = 85th \ percentile \ rank$$
 (1.1)

Within a LCC, a frequency distribution of pixel NPP values is used to estimate the condition of each pixel (spatial resolution=  $250m^2$ ) relative to the potential NPP. NPP loss is calculated as the difference between the potential NPP (pNPP) and observed NPP (oNPP). This actual loss in NPP is recorded in units of gC\*m<sup>-2</sup>\*yr<sup>-1</sup>. The lower values (i.e. sites with negative deviations in NPP) from the frequency distribution are the pixels that may have suffered degradation. The proportional change in NPP may also be recorded. This is the percent difference in observed NPP (oNPP) from the potential NPP (pNPP) which may be compared across the LCC.

$$Absolute NPP \ loss = oNPP - pNPP \tag{1.2}$$

$$Percent NPP \ loss = \frac{oNPP - pNPP}{pNPP} \times 100\% \tag{1.3}$$

Annual LNS results within the LCC are then summarized through the duration of the study period. This is done by averaging each estimate of relative NPP loss at each pixel through all years investigated.

The preceding steps are then repeated for all LCC within the study region. This procedure results in the generation of a spatial representation (e.g. a map) of mean NPP loss for all years assessed. Regional patterns of land degradation may be compared across classes using the proportional change in NPP. The total NPP loss, recorded in units of  $gC^*m^{-2*}yr^{-1}$ , is calculated within each land cover class and across the study region. Interpretation of results obtained using the LNS approach is dependent on identification of appropriate reference sites. This requires comprehensive investigation (e.g. field

assessment or against similar measures of potential) of sites estimated as potential NPP, as spuriously high values may result from the erroneous inclusion of areas where NPP is influenced by environmental factors not normalized in the definition of regional environments (e.g. wetland and riparian ecosystems and commercial irrigation). High spatial resolution satellite and aerial photographs ( $<30m^2$ ) can be used in this assessment.



1.4. Study Area

For this dissertation, the process of reduced vegetation production will be studied in the Burdekin Dry Tropics (BDT) region. An extensive degradation history in the Burdekin exemplifies the sensitivity of vegetation in the wake of poor land use management [22]. The nearly uniform land use practice of livestock grazing in the BDT allows for comparisons of the effects of varied land use intensity [29,113]. Examination of temporal trends derived from the Enhanced Vegetation Index (EVI) from MOD13Q1, suggest the Burdekin is exhibiting sustained negative trends in overall plant greenness [114]. The variety of soil and vegetation types as well as the steep climatic gradients across the region makes the BDT representative of other Australian grazing lands. This will allow for the extrapolation of findings to similar dryland areas throughout Australia and the world.

The BDT region, covering approximately 133,432km<sup>2</sup>, consists of a largely flat terrain slowly increasing in elevation inland with major rivers flowing largely into the Burdekin River and ultimately eastward toward the Pacific coast [113,115,116]. Six large river basins are contained in the BDT (Figure 1.3): The Upper Burdekin  $(2.26 \times 10^6 \text{ km}^2)$ , Belyando (2.08 x10<sup>6</sup> km<sup>2</sup>), Cape Campaspe (1.18x10<sup>6</sup> km<sup>2</sup>), Suttor (1.07x10<sup>6</sup> km<sup>2</sup>), Bowen Broken Bogie  $(0.63 \times 10^6 \text{ km}^2)$  and Lower Burdekin  $(0.23 \times 10^6 \text{ km}^2)$ . More than 70% of rainfall falls during summer months (December-February), runoff variability is high [117,118], and discharge from rivers and creeks are characterized by large pulses of water of short duration associated with wet season rains [119]. Seasonal rainfall totals show great range, 400-1500mm annually. Although regular winter rainfall is experienced throughout the BDT, a sharp decreasing gradient in seasonal rainfall exists away from the coast [115]. During the study from 2000 to 2013, years with low (e.g. 2002-2007 & 2013;  $\leq$  500mm year<sup>-1</sup>) and high (e.g. 2000-2001 & 2008-2012;  $\geq$  600mm year<sup>-1</sup>) accumulations occurred. The variation in weather provides an opportunity to determine how well fundamental factors related to reduced productivity can be separated (i.e. anthropogenic and natural).

In the BDT, NPP is strongly influenced by regional variations in moisture availability (Hutley et al., 2000), fire frequency (Beringer et al., 2007), and soil properties. Native vegetation varies from dense to sparse forest to shrub-land and open grassland. Approximately 83% of the BDT is savanna consisting of mixed grass and trees. There are smaller areas that consist exclusively of shrubs (1%), grasses (8%), or rain-fed crops (8%). The ratio of tree-to-grass cover is a defining attribute that differentiates local environments in savanna ecosystems [120]. The croplands, both irrigated and rain-fed, are found in northeastern, higher rainfall areas.

Table 1.1 Regional survey of land management practices in the Burdekin Dry Tropics region in Y2001-2. Grazing land management was evaluated and assigned to one of four categories: Good management indicates sustainable land use. Poor management indicates sustainable land use. Poor management indicates sustainable land use. Poor management indicates land use likely to damage land condition and lead to degradation. Current land management suggests possibility for more sites to enter poor land condition. Modified from <a href="https://www.brs.gov.au/landuse">www.brs.gov.au/landuse</a>.

Burdekin Dry Tropics	Grazing Land Management Categories				
	Good	Above	Below	Poor	
		Average	Average		
Number of grazing rangeland owners	46	271	406	104	
Percentage of grazing rangeland owners	6%	33%	49%	12%	

Livestock grazing has been the major land use, accounting for between 85-90% of the land use in sub catchments within the BDT, since European settlement and is dominated by extensive grazing (primarily cattle) on natural, unimproved pastures [113]. An estimated 827 landholders graze cattle on 128,000km<sup>2</sup> (Table 1.1; [113]). Approximately 12% of these graziers, on rangeland occupying over 16,192km<sup>2</sup>, use management practices reported by the Australian government as likely to result in land degradation (Table 1.1; www.brs.gov.au/landuse). In addition, nearly 23% of surveyed graziers self-report significant symptoms of degradation in Y2001-Y2002 (ABARE), suggesting future scenarios of land degradation (C or D; [1]).

#### 1.4. Research Goals

The overall goal of the dissertation is to assess reductions in NPP in a semi-arid region at a regional scale (14 million hectares), which are associated with the process of anthropogenic land degradation. It is hypothesized that land degradation resulting from human factors on the landscape may irreversibly reduce NPP below the potential set by environmental conditions.

Identifying spatially explicit patterns of reduced productivity at regional scales is expected to provide an indicator of the current state of rangeland systems. Persisting reductions in pasture productivity will be detected through the mapping of spatial distributions of NPP from Y2000 to Y2013. Locations exhibiting significant and persistent reductions in production from its potential may be indicative of degradation, natural or otherwise. It is also hypothesized that resulting anthropogenic reductions in NPP are distinguishable from natural, spatial and temporal, variability in NPP.

Examining vegetation responses to inter-annual weather patterns will distinguish the short-term effects of weather (e.g. rainfall, temperature) from long term trends of vegetation condition. Potential vegetation production will be used to provide a reference for vegetation response to weather. Deviations in NPP from this reference response of vegetation to weather will be used to identify and quantify reduced productivity. Exploration of long term trends in deviations in NPP may reveal distinct transitions in vegetation condition. Persistent negative trends will be used to indicate active land degradation.



Figure 1.4 Rainfall variation in the Burdekin Dry Tropics region in Queensland, Australia. Note: Rainfall from during drought years (i.e. 2004 to 2007) and during non-drought years (i.e. 2008 to 2011) were investigated (symbolized with darkened bars). Dashed line represents 14-year average.

The relationship between degradation and fractional vegetation cover is not well understood and will be explored. As a key characteristic of land surface function, fractional vegetation cover will improve the understanding of degradation extent and severity. Fractional cover may also inform about rehabilitation and/or mitigation strategies for areas undergoing

degradative processes. Fractional cover was used to distinguish land areas with live and dead cover from those that were bare. The presence of dead, brown vegetation, as opposed to bare exposed soil, has numerous beneficial properties including the deceleration of erosion. Here it is hypothesized live, green vegetation cover will have the strongest correlation to remotely sensed measurements of NPP and modeled estimates of degradation. Furthermore, it is hypothesized that the spatial and temporal extents of dead, brown vegetation cover will be positively correlated to degradation.

Degradation that is measured using NPP as its proxy has implications for both above and below ground carbon storage. However, the impact that degradative processes have on above ground vegetation production (i.e. vegetation biomass) holds the most relevance to secondary biological production, food availability, and ultimately regional management. A highly parameterized mechanistic model will be used to simulate biomass under varying degradation conditions (i.e. non-degraded and degraded). Therefore, vegetation biomass and its accumulation over time are important indicators of degradation severity. Here it is hypothesized that biomass and its accumulation in time will be strongly correlated with varying severities of degradation. Additionally, coupled environment and degradation relationships are not well understood but are crucial to understanding land condition. The interaction between degradative processes and controlling environmental factors (e.g. rainfall) are essential for proper characterization of vegetation degradation. It is hypothesized that a relationship between degradation and controlling environmental factors (e.g. rainfall) exists wherein degradation characteristics (e.g. severity, extent) will respond to the variability in environment factors.

Human factors are predicted to show a relationship with reductions in NPP not related to the natural environment. Indicators of land management type and intensity will be explored at these sites. Land use pressure and spatial and temporal NPP loss will be compared. Those comparisons may aide in the diagnosis of broad land use management practices present at sites which have undergone the process of land degradation.

#### **1.5. Research Strategy**

The goals of the dissertation are to (1) identify the extent and severity of degradation using productivity as the primary surrogate, (2) compare the degradation of productivity to other known mechanisms of degradation, and (3) relate the expression of degradation to components of vegetation and varying environmental conditions. The following questions and objectives will be addressed:

*Research Question 1:* Is there evidence of human-induced degradation of NPP?
 Objective 1 (O1): Identify potential NPP within environmentally homogeneous regions using spatially explicit references.

- **Objective 2 (O2):** Identify and characterize the spatial extent of persistent reductions in NPP at the regional scale.
- **Objective 3 (O3):** Classify and quantify the states and trends of anthropogenic degradation.
- Research Question 2: Are non-green components of vegetation sensitive to degradation?
  - **Objective 4 (O4):** Compare components of fractional cover to degradation extent, severity and trends.
  - **Objective 5 (O5):** Quantify spatial reductions in fractional cover and link to management practices.
- Research Question 3: Are the effects of degradation on NPP related to land use and do environmental factors interact?
  - **Objective 6 (O6):** Correlate simulations of biomass and pasture growth with anthropogenic degradation.
  - **Objective 7 (O7):** Investigate characteristics of degradation under drought and non-drought conditions.

The overall information flow and strategy of the dissertation is presented in Figure 1.5. While the major research questions are addressed throughout the dissertation, the goals correspond to dissertation chapters (i.e. Goal 1 to Chapter 2, Goal 2 to Chapter 3, and Goal 3 to Chapter 4).



Figure 1.5 Simplified schematic of research plan. Research objectives O1, O2, & O3 are addressed in Question 1; objectives O4 & O5 in Question 2, and objectives O6 & O7 in Question 3.

its' global extent and severity, conflicting definitions and indicators and background on phenomena in Australian rangelands. Finally, the research plan is presented with three major research questions and their associated objectives and goals.

In Chapters 2 to 4, three studies are presented that improve the current understanding of degradation and its dynamics. Each chapter corresponds to a major research goal (presented in 1.5).

In Chapter 2, the degradation of net primary production is identified, mapped and analyzed. This study employs the Local NPP Scaling (LNS) approach to identify patterns of anthropogenic degradation of NPP in the Burdekin Dry Tropics (BDT) region of Queensland, Australia from 2000 to 2013. The method starts with land classification based on the environmental factors presumed to control (NPP) to group pixels having similar potential NPP. Then, satellite remotely sensing data is used to compare actual NPP with its potential. The difference in units of mass of carbon and percentage loss were the measure of degradation. The entire BDT (7.45x10<sup>6</sup> km<sup>2</sup>) was investigated at a spatial resolution of 250x250m.

In Chapter 3, other components of vegetation are investigated and compared to degradation of NPP. This chapter attempts to address the lack of information regarding the effect of degradation on the non-photosynthetic components of vegetation (e.g. wood, stems, leaf litter) and the relationship between photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare soil under degraded conditions. The major objective of the study is to evaluate regional patterns of fractional cover (i.e. PV, NPV, BS) under degraded and non-degraded NPP conditions in a managed rangeland in north Queensland, Australia, with specific emphasis on five example locations. Homogenous

environmental conditions were identified and each of NPP, PV, NPV, and BS are scaled according to their potential, reference values.

In Chapter 4, a prognostic model is used to compare biomass and pasture growth to degradation. Live and dead components of biomass are explored for their response to degradation throughout the growth cycle. The effects of management are also tracked through known land management patterns and utilization parameters that are included in simulations of biomass. The study is conducted in a single grazing property where management practices are uniform. Also, the symptoms of degradation are investigated under varying rainfall conditions (i.e. drought and non-drought).

In Chapter 5, a synthesis of all the research findings is presented. The chapter begins with providing the context for the assessment of degradation. Key findings and a recapitulation of research questions are presented next. An in-depth discussion regarding the science of degradation monitoring follows. Finally, possible directions for future work are outlined.

# Chapter 2 Degradation of Net Primary Production 2.1. Introduction

Land degradation is a deleterious process in which unfavorable conditions for humans occur [3,5,49,61] as a result of direct and indirect human and natural processes. In drylands (aridity index < 0.65), poor land management such as excessive cultivation, overgrazing and unmanaged fires have far reaching effects on biogeophysical processes [7]. While degradation is always undesirable, there is evidence that, in some cases, it cannot be reversed [121] when the causes are removed – a much more serious outcome. However, it is not known how widespread this condition is. There are many other aspects of dryland degradation that are little understood, including its location, severity and actions needed for remediation [60,111] or, at least, to prevent a net increase [122,123]. The extent of soil or pasture degradation through overgrazing, anywhere in the world, has been estimated by experts' subjective opinion, rather than systematic quantitative criteria [124].

'Degradation' implies an undesirable condition compared with a starting point [121] but degraded compared to what? To detect a relative condition, a reference is needed, in this case not degraded [36,65,125,126] without which states of degradation have no meaning. However, the detection of non-degraded reference sites that are at their potential is problematic [63]. There are several approaches that seem reasonable but have severe limitations, particularly when applied to large areas: visual assessment of satellite imagery is entirely subjective and therefore unrepeatable; field surveys, such as the National Resources Inventory [127], are limited to small areas [47,128,129] that can be assessed by an evaluator on the ground; process modeling of potential production
followed by comparison with actual production [130,131] suffers from the need for data and parameters that are generally not available [7].

The particular type of degradation investigated here is anthropogenic reduction of net primary production (NPP) which, in addition to its own importance, is an indicator of a wider range of degradative processes [7] such as soil compaction, salinization, water and wind erosion that generally also reduce NPP [55,61]. The objective of this study was to identify and characterize the extent and severity of degradation of vegetation productivity in the extensive rangelands, in excess of 10,000 km<sup>2</sup>, of the Burdekin Dry Tropics (BDT) in Queensland, Australia. The Local NPP Scaling (LNS) method [47,48,64] was used to address the problem of identification of reference sites. LNS starts with classification of the region into land capability classes (LCCs) in which the biogeophysical environment is, as near as possible, the same, so assessments are made with areas of the same type and potential. The reference NPP is identified as the maximum value in each LCC, then the comparisons are made with this standard. Inaccuracies and even invalidity of the LNS technique can arise under certain conditions, although some methods are available that can minimize these, but they can never be entirely prevented. On the other hand, bearing in mind the fundamental requirement for non-degraded comparison, and also that there is currently no other method available, LNS was used.

Specifically, this study: (1) identified the spatial extent of non-degraded and degraded land; (2) distinguished significant land trends in inter-annual reductions in NPP; and (3) linked total NPP reductions to specific land processes and states in the BDT.



Figure 2.1 Location of the Burdekin Dry Tropics (BDT) region in the State of Queensland, Australia, the six major river basins, and major roads and towns.

accumulations occurred (Figure 2.2).

## 2.2.1 Land capability classification

Land capability classes (LCCs) are areas that are homogeneous with respect to the selected environmental factors. The factors used here were meteorological, soil, and vegetation. The Australian Bureau of Meteorology distributes daily, synoptic weather reports consisting of rainfall [132], minimum and maximum temperature, water vapor pressure deficit at 9am and 3pm, and solar exposure [133], gridded at 5x5km spatial resolution. Daily inputs were summed for the growing season from November to April and rescaled to 250x250m using a nearest-neighbor interpolation. Data from three national scale, 1x1km, gridded, soil property maps [134]were used: (1) plant available water-holding capacity, calculated as the sum of the water-holding capacity of the A and

2.2. Materials and Methods 2.2.1 Study area The entire BDT was investigated for degradation. Six large river basins are contained in the BDT (Figure 2.1): the Upper Burdekin (2.26x10<sup>6</sup> km<sup>2</sup>), Belyando (2.08 x10<sup>6</sup> km<sup>2</sup>), Cape Campaspe (1.18x10<sup>6</sup> km<sup>2</sup>), Suttor (1.07x10<sup>6</sup> km<sup>2</sup>), Bowen Broken Bogie (0.63x10<sup>6</sup> km<sup>2</sup>) and Lower Burdekin (0.23x10<sup>6</sup> km<sup>2</sup>). During the study from 2000 to 2013, years with low (e.g. 2002-2007;  $\leq$  500mm year<sup>-1</sup>) and high (e.g. 2008-2012;  $\geq$  600mm year<sup>-1</sup>) B soil horizons (0 to 1m); (2) clay content (0 to 0.3m); and (3) soil bulk density (0 to 0.3m, spanning A and B horizons) as a measure of porosity. Foliage projective cover (FPC) was obtained from Danaher et al. [135] although it was only available for one year prior to the study period. Pixels with over 50% FPC (mostly dense tropical forest) were not included.

A k-means unsupervised clustering was used to classify meteorological data, soil properties, and FPC for each growing season. To ensure equal numerical weighting, all environmental data were normalized prior to clustering. The environmental data were then partitioned using unsupervised clustering (n=50, maximum iterations = 100, change threshold = 0.05%, minimum of 1,000 pixels), which resulted in 50 clusters. These are referred to as UMD Land Capability Classes (UMDLCC). The pixels found within each homogeneous UMDLCC were examined using linear regression and Person correlation to determine if any underlying relationships remained between NPP and the environmental data used to create them. Only LCCs where the correlation was below 0.4 were included in the final UMDLCC for that year. Pixels with correlations above 0.4 were reclassified. This procedure was repeated for each year.

Few maps exist that could be used for validation of the homogeneity of LCCs in the BDT. One such is the Grazing Land Management (GLM) Land Types [136,137] which classifies areas based on vegetation, soil, and terrain characteristics to create static types within which the response to grazing pressure is similar. Since the principles used to create GLM were similar to those of the UMDLCCs, an additional LNS was performed using GLM land types (GLMLCC). The vector GLM map was converted to a raster format at a 250x250m spatial resolution. GLM land types consisting of fewer than

1,000 pixels were removed, resulting in 50 GLMLCCs – the same number of LCCs as the UMDLCC. These were compared with the UMDLCC.

The two LCCs were compared using the mean square variance of their maximum NPP to





determine the extent to which each reduced within-LCC variance and maximized between-LCC variance. Inter-annual wet season rainfall (Nov to Apr) was averaged throughout the BDT (Figure 1.3), and then compared with the two variance components of both UMDLCC and GLMLCC. A paired t-test was used to determine whether there were significant differences in within-LCC and between-LCC variance in maximum NPP for the two LCCs.

A second comparison was made using the Vegetation Assets, States and Transitions (VAST) classification of Australia, version 2 [138]. VAST is a national level map of changes to vegetation since European settlement, which began in 1750, showing the degree of anthropogenic modification of native vegetation until 2011. VAST uses the following classes: wilderness, biophysical naturalness, land use, land cover, and extent of native vegetation. There are four classes of increasing human modification: 1-'modified', 2-'tranformed', 3-'replaced', and 4-'removed'. Areas without naturally occuring native vegetation are designated 5-'bare' and areas with no change as 0-'residual'. Erosion is strongly linked to land degradation in drylands [8,139], and this is the case in Australian rangelands [140-144]. A datbase of erosion was used to better understand the nature of the degradation that was detected. Four environmental variables related to natural and human-related erosion processes were used: sediment load at 500x500m [145]; soil erodibility, rainfall erosivity and hillslope erosion, each at 250x250m [146]; and gully density at 500x500m [147]. Gully density and sediment load were downscaled from their original spatial resolutions to 250x250m using a nearest-neighbor interpolation.



Figure 2.3 Example of the use of the frequency distribution of NPP of pixels in a single LCC to calculate LNS values. The vertical line denotes the reference NPP at the 85 percentiles of the distribution. The abscissa is labelled in LNS, NPP, and percent LNS units.

### **2.2.2. Measurement of NPP using satellite data** Moderate Resolution Imaging Spectrometer (MODIS) NPP data (MOD17A3)

[148] were obtained from the Land Processes Distributed Active Archive Center satellite data archives (http://modis.gsfc.nasa.gov/data/; *accessed 06/05/2014*). These data have 1x1km resolution and so, to maintain the highest possible spatial resolution, the data were rescaled to 250x250m using coefficients of the regression of growing season 250x250m NDVI (MOD13Q1) on 1x1km, NDVI (MOD13A2).

LNS is spatially and temporally scale-dependent since the NPP in a pixel is the sum of its finer scale components, similarly for the individual years in the 14 years that were studied may be different. Therefore, in this application, degradation at finer spatial and temporal scales than 250x250m and 14 years may have been missed, as would any pattern of LNS at finer scales (such as confinement of degradation to small, but repeated ridges in a tributary). While this might be a drawback for fine scale applications, such as the effects of livestock congregation at water and gates, in the BDT, livestock management is normally applied to areas large enough to contain at least several 250x250m pixels. Other limitations for which there are no perfect solutions include the effect of gradients in environmental factors, such as meteorological variables, that are dissected by the classification into arbitrary ranges. Pixels are more likely to be selected as the potential sites if they are in the most favorable part of the gradient, often at the edge of LCC. While this effect is minimized using a large number of LCCs, it cannot be removed entirely. A warning situation would be if reference pixels were confined to one part of an LCC. In all of these cases, care is needed to review the LCCs using alternative sources such as high-resolution imagery that can provide visual warning. Additional limitations can arise if small features occur that are not large enough to be placed in a

different LCC, also the situation where the entire LCC is degraded or entirely nondegraded. Various methods can be used to minimize these and other problems, but they cannot all be entirely prevented and in some cases the extent of the effect cannot be measured.

### 2.2.3. Local net primary production scaling (LNS)

LNS values are the difference between each pixel and its reference NPP (Figure 1.3). It is therefore zero (equal to the reference NPP, i.e. not degraded) or negative (below the reference, i.e. degraded). The LNS values can be expressed as the actual reduction of NPP in gC m<sup>-2</sup> year<sup>-1</sup> or as a percentage of the reference. LNS was calculated for each year (2000-2013), producing 14 LNS maps, using both the UMDLCC and GLMLCC maps.

The potential, non-degraded reference NPP was obtained using the frequency distribution of NPP in each LCC (Figure 2.3). The 85<sup>th</sup> percentile was arbitrarily selected as the best estimator. Pixels with NPP higher than the reference, possibly caused by residual pixels with high NPP in areas that were not typical of the rest of the LCC, were omitted. A possible limitation of LNS is if no pixels are at their maximum; then the reference would be below the true potential. Masking rivers, open water, roads, human settlements, and other human land features not representative of the LCC minimized this effect, but it cannot be entirely eliminated and so interpretation of the results must take this into account.

LNS percent values were averaged from 2000 to 2013 to determine the mean NPP reduction for each pixel over the 14 years. To facilitate discussion, values that were  $\leq$  - 30% were arbitrarily classified as 'degraded'. All other pixels, those where LNS was between 0% and -29% were classified as 'non-degraded'. A time-series of annual LNS

percent values for every pixel was used to identify significant ( $\alpha$ <0.10) inter-annual trends in LNS over the 14-years. Pixels were classified according to their trends into three categories: (1) no significant inter-annual trends ('no LNS trend'); (2) significant positive inter-annual trends ('positive LNS trend'); and (3) significant negative interannual trends ('negative LNS trend'). The trend classification was combined with the two levels of degradation to create six classes: (1) 'non-degraded and positive LNS trends', (2) 'non-degraded and no LNS trend', (3) 'non-degraded and negative LNS trend', (4) 'degraded and positive LNS trend', (5) 'degraded and no LNS trend', and (6) 'degraded and negative LNS trend'.

Spatial agreement between average LNS values and ecological indicators related to land condition (e.g. hillslope and gully erosion) or susceptibility to poor condition (e.g. rainfall erosivity and soil erodibility) were examined using Cohen's kappa (k) fuzzy numeric [149]. This elaboration of the simple kappa test includes 'near misses' and accounts for coincidences that occur by chance. Values range from 0.0 to 1.0 with increasing agreement. All kappa calculations were performed using the Map Comparison Kit [150].

### 2.3. Results 2.3.1. UMDLCC



Figure 2.4 Mean square variance in reference NPP (MgC m-2 year-1) for UMDLCC and GLMLCC in relation to rainfall; (a) 'within-LCC' and (b) 'between-LCC' with best-fit regression lines for each year 2000 to 2013.

The average number of pixels per UMDLCC varied each year from 3,182  $(0.01 \times 10^6 \text{ km}^2)$  in 2004 to 141,690  $(0.56 \times 10^6 \text{ km}^2)$  in 2013. Their locations differed each year owing to inter-annual differences in weather patterns. Approximately half were non-contiguous, interspersed between other LCCs, but generally in no more than two river basins. Most reference pixels were selected in more than one year and a small number were selected in all years.

The inter-annual, between-LCC variance in reference NPP was higher for UMDLCC compared with GLMLCC. Conversely, within-LCC variance for UMDLCC was lower than for GLMLCC, indicating that the pixels selected as reference within UMDLCCs were more homogeneous than GLMLCC and more distinct between. A paired t-test showed that these differences were significant (Table 2.1), Inter-annual rainfall was significantly related to between-LCC and within-LCC

variance in reference NPP for both LCCs (Figure 2.4), accounting for nearly equal

proportions of within-LCC variance in reference NPP for UMDLCC and GLMLCC

(Figure 2.4b), but between-LCC variance was better accounted for by UMDLCC (81%)

than for GLMLCC (66%; Figure 2.4a).

**Table 2.1.** Mean, standard deviation, and t-test of mean square variance of reference NPP (gC m<sup>-2</sup> year<sup>-1</sup>) for UMDLCC and GLMLCC, partitioned into between-LCC and within-LCC.

Mean square	UMDLCC Mean Std deviation		GLMLCC		<u> Cignificance loval</u>	
variance			Mean	Std deviation	Significance level	
Between LCCs	4.15 x 10 <sup>8</sup>	1.1 x 10 <sup>8</sup>	1.76 x 10 <sup>8</sup>	0.5 x 10 <sup>8</sup>	t <sub>13</sub> =12.6 p<0.0001	
Within LCCs	$4.38 \times 10^4$	1.1 x 10 <sup>4</sup>	7.71 x 10 <sup>4</sup>	2.3 x 10 <sup>4</sup>	t <sub>13</sub> = 9.6 p<0.0001	

**Table 2.2.** Average LNS (Mg C  $m^{-2}$  year<sup>-1</sup>) in the Burdekin Dry Tropics (BDT) region for all six combinations of degraded and non-degraded LNS conditions and three inter-annual LNS trends – no trend, positive and negative trends. The percentage of BDT area in each land condition is shown in parentheses.

Trand catagory	Degradation condition (Mg C m <sup>-2</sup> year <sup>-1</sup> )					
Trenu category	Non-degraded LNS	Degraded LNS	Average			
No LNS trend	-1.70 (65.3%)	-3.85 (14.1%)	-2.08 (79.4%)			
Positive LNS trend	-1.90 (10.0%)	-3.95 (3.6%)	-2.44 (13.6%)			
Negative LNS trend	-1.48 (5.0%)	-4.14 (2.0%)	-2.24 (7.0%)			
Average	-1.71 (80.3%)	-3.90 (19.7%)	-2.14 (100%)			

Table 2.3. Area and percentage of Burdekin Dry Tropics in each LNS range.

		· · ·		
Degradation	INS Pango	Total area (km <sup>2</sup> ) and	Total reduction in NPP (GgC)	
Condition	LINS Kallge	percent of BDT		
Non	0 to -9%	1.12x10 <sup>6</sup> (15.8%)		
degraded	-10 to -19%	2.40x10 <sup>6</sup> (33.9%)	-1.9 (80.3%)	
	-20 to -29%	2.10x10 <sup>6</sup> (29.6%)		
	-30 to -39%	0.96x10 <sup>6</sup> (13.6%)		
Degraded	-40 to -49%	0.35x10 <sup>6</sup> (5.0%)	1 1 (10 70/)	
	-50 to -59%	0.10x10 <sup>6</sup> (1.5%)	-1.1 (19.7%)	
	-60 to -69%	0.03x10 <sup>6</sup> (0.4%)		

-7	-70 to -79%	0.01x10 <sup>6</sup> (0.1%)
	< -80	0.00x10 <sup>6</sup> (<0.0%)

The comparison of UMDLCC and the VAST land classification, albeit based on different data and aims, provided an independent comparison. 35.8% of UMDLCC reference pixels were in the VAST 'residual' class that has, theoretically, been undisturbed since 1750. The remaining 64.2% were in classes with varying degrees of vegetation changes from native pasture: 1-'modified' (29.6%); 2-'transformed' (19.2%); and 3-'replaced' (15.3%). The remaining reference sites, less than one percent, were in the 4-'removed' or 5-'bare' classes with LCCs where all pixels were degraded, or have been caused by inadequate or inaccurate data used to create the LCCs, errors in the VAST classification, or a result of re-gridding VAST pixels from 1x1km to 250x250m spatial resolution.

### 2.3.2. LNS

The -30% LNS percent value used to differentiate 'degraded' areas from 'nondegraded' areas was equivalent to an average annual reduction in NPP of -169.6 gC m<sup>-2</sup> year<sup>-1</sup> (standard deviation=25.5). Between 2000 and 2013 the average annual LNS across the entire BDT, including both 'degraded' and 'non-degraded' areas, was -2.14 MgC m<sup>-2</sup> year<sup>-1</sup> (Table 2.2). The average reduction in 'degraded' areas was more than twice that in the 'non-degraded' areas and the LNS of the positive LNS trend class was lower than the negative and no LNS trends.



Figure 2.5 LNS in BDT (a) & enlargements of the areas indicated in (a): (b) high/low LNS on either side of a station boundary; (c) variation within a single station showing gradients from low to high; (d) low LNS in eroded drainage area; (e) hillslope erosion resulting in bare surface with little to no vegetation cover; (f) area of tree removal with visible erosion and reduced cover. Black lines are the boundaries of river basins and red lines are station boundaries.

The sum of LNS values for an entire class, as opposed to the LNS value per unit area, revealed the importance of class size in contributing to the overall reduction in NPP. The 'degraded' class had a total reduction in NPP of -1.1 GgC from 2000 to 2013 and occupied 1.46x10<sup>6</sup> km<sup>2</sup> (Table 2.3). The larger area occupied by the 'non-degraded' class resulted in a greater total reduction in NPP (-1.9 GgC; Table 2.3), although much less severe reduction in NPP per unit area (Table 2.2). In the same way, non-degraded areas

with no LNS trend were by far the greatest total reduction in NPP owing to the large area occupied by this class.

The majority of degraded pixels had LNS values between -30% and -49%, with only a small proportion below -50%. The largest number of the non-degraded pixels were in the -10% to -29% LNS classes. For the degraded pixels, the average LNS in NPP units was less than half that of the non-degraded pixels (Tables 2.4 & 2.5). Similarly, reductions in NPP as a percent of the reference were lower (more severe) for degraded than non-degraded pixels.

River basin (in decreasing order of area)	Total area in km <sup>2</sup> and percent of the class	Average LNS in gC m <sup>-2</sup> year <sup>-1</sup>	Average LNS as a percentage of reference NPP
Upper Burdekin	2.28x10 <sup>5</sup> (16%)	-225.3 (sd=42.8)	-36% (sd=6)
Belyando	6.60x10 <sup>5</sup> (45%)	-200.2 (sd=47.5)	-40% (sd=8)
Cape Campaspe	2.05x10 <sup>5</sup> (14%)	-205.3 (sd=45.6)	-39% (sd=9)
Suttor	3.17x10 <sup>5</sup> (22%)	-215.3 (sd=52.0)	-40% (sd=9)
Bowen Broken	0.33x10 <sup>5</sup> (2%)	-225.7 (sd=45.7)	-36% (sd=7)
Bogie			
Lower Burdekin	0.25x10 <sup>5</sup> (2%)	-226.7 (sd=55.1)	-38% (sd=8)
Entire BDT region	14.79x10 <sup>5</sup> (100%)	-209.1 (sd=48.7)	-39% (sd=8)

**Table 2.4.** Degraded LNS class. Area, severity, and variation in LNS and LNS percent. sd – standard deviation

### 2.3.3. Spatial variation in LNS

The extent of 'degraded' and 'non-degraded' areas varied between the six major river basins (Tables 2.4 & 2.5). Two of these, Belyando and Suttor, comprised 67% of all 'degraded' areas in the entire BDT while the Bowen Broken Bogie had the lowest (2%) (Table 2.4). Despite being the first and third largest basins in the BDT ('degraded' plus 'non-degraded' pixels) the Upper Burdekin and Cape Campaspe had only the third and fourth most 'degraded' pixels (Table 2.4), respectively. However, 'non-degraded' area decreased with decreasing size of each river basin (Table 2.5). The severity of reductions in NPP, indicated by the average LNS, varied surprisingly little between river basins (Tables 2.4 & 2.5). The most severely degraded were in the Lower Burdekin, Bowen Broken Bogie, and Upper Burdekin (Table 2.4). The Upper Burdekin also had the most severe reductions of non-degraded pixels (Table 2.5). The Belyando and Cape Campaspe had the least severe reductions in NPP of degraded and non-degraded pixels, respectively. The average LNS and its percentage of the reference NPP for degraded and non-degraded pixels, however, were all within one standard deviation; suggesting that the reductions in NPP for each river basin did not differ substantially.

**Table 2.5.** Non-degraded LNS class. Area, severity, and variation in LNS and LNS percent. sd – standard deviation

River basin (in	Total area in km <sup>2</sup>	Average LNS in	Average LNS as a
decreasing order	and percent of the	Average LNS III $\sigma C m^{-2} v cor^{-1}$	percentage of
of area)	class	ge ni year	reference NPP
Upper Burdekin	20.34x10 <sup>5</sup> (34%)	-105.3 (sd=45.0)	-17% (sd=7)
Belyando	14.15x10 <sup>5</sup> (24%)	-92.2 (sd=39.2)	-18% (sd=7)
Cape Campaspe	9.74x10 <sup>5</sup> (16%)	-88.3 (sd=41.2)	-16% (sd=8)
Suttor	7.57x10 <sup>5</sup> (13%)	-97.4 (sd=41.2)	-18% (sd=8)
Bowen Broken	$6.01 \times 10^{5} (100/)$	00.6(cd-10.8)	15% (cd-7)
Bogie	0.01X10*(10%)	-99.0 (Su-49.8)	-13% (SU-7)
Lower Burdekin	2.03x10 <sup>5</sup> (3%)	-95.4 (sd=49.5)	-15% (sd=8)
Entire BDT region	59.83x10 <sup>5</sup> (100%)	-97.5 (sd=43.9)	-17% (sd=7)

Among degraded areas there was evidence of managed grazing, including abrupt

differences in LNS along station boundaries (Figure 2.5b), but there were also gradients of LNS within a single station (Figure 2.5c), and others with low LNS spread across multiple boundaries (Figure 2.5d). Other areas with evidence of management included forest clearing (Figure 2.5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 2.5f).

#### 2.3.4. Inter-annual trends in LNS

Across the entire BDT there was substantial inter-annual variation in LNS,

particularly in areas with low values (Figure 2.6a). In years with high rainfall (e.g. 2000, 2008, 2009 and 2011) compared with low rainfall (e.g. 2003, 2005 and 2013), there were fewer pixels with low LNS, but the severity of reductions was greater. In areas with little topographic variation, such as the central BDT, there was more spatial variation in low values between years. Positive trends were found predominately in the western and southern Upper Burdekin and southern Belyando basins. Negative trends were most common in the northern Belyando, central Upper Burdekin, and southern Suttor river basins. 79.4% of the BDT had no significant trend in LNS.



Figure 2.6 Time-series of maps of the Burdekin Dry Tropics from 2000-2013 showing (a) annual LNS percent values from 2000 to 2013 and (b) inter-annual trends in LNS classified into negative, positive, and no LNS trend.

The magnitudes of negative and positive inter-annual trends in LNS varied substantially between river basins (Figure 2.6b, Tables 2.6 & 2.7). The Suttor had by far the lowest negative trends (but the largest standard deviation; Table 2.6). The Upper

Burdekin and Cape Campaspe had the least negative trends (Table 2.6). Positive trends were highest in the Bowen Broken Bogie and lowest in the Belyando (Table 2.7).

Some patches of positive and negative LNS trends were found in large areas that spanned multiple river basins (Figure 2.6b). These may have been a result of environmental conditions (e.g. low rainfall, soil properties) in some combination other than that used to create the LCCs, or a single variable not used in the classification, that crosses the LCC boundaries, for example, more friable soils.

There were strong contrasts in the average LNS of the negative and positive trend classes between river basins (Tables 2.6 & 2.7). The average LNS of negative trends in the Suttor was nearly twice that of the Upper Burdekin. The Suttor river basin had most severe LNS reductions in the negative trend class (Table 2.6). On average, for negative trends, the Bowen Broken Bogie, Upper and Lower Burdekin had the least severe reductions in NPP while the most severe were in the southern river basins: Belyando, Cape Campaspe, and Suttor (Table 2.6). Surprisingly, the Belyando had less severe reductions in NPP in areas with negative trends (Table 2.6) than in areas with positive trends (Tables 2.7). In the Belyando, the percent LNS for positive trends were less than -30%, suggesting that numerous low LNS values were found among positive trends.

Divon basin (in	Total area in km <sup>2</sup>		Average LNS in gC
docrossing order	and percentage of	Average trend in	m <sup>-2</sup> year <sup>-1</sup> and as a
of area)	those areas with	gC m <sup>-2</sup> year <sup>-1</sup>	percentage of
01 al ea j	negative trends		reference NPP
Upper Burdekin	1.26x10 <sup>5</sup> (24%)	-7.3 (sd = 2.8)	-102.0 (-16%)
Belyando	2.10x10 <sup>5</sup> (40%)	-8.4 (sd = 3.3)	-134.0 (-27%)
Cape Campaspe	0.71x10 <sup>5</sup> (14%)	-7.5 (sd = 2.6)	-131.7 (-24%)
Suttor	0.77x10 <sup>5</sup> (15%)	-13.8 (sd = 10.0)	-184.2 (-34%)
Bowen Broken	0.22x10 <sup>5</sup> (4%)	-9.7 (sd = 6.0)	-95.0 (-14%)
Bogie			
Lower Burdekin	0.15x10 <sup>5</sup> (3%)	-9.5 (sd = 5.6)	-116.0 (-17%)
Entire BDT region	5.21x10 <sup>5</sup> (100%)	-8.9 (sd = 5.4)	-120.5 (-25%)

**Table 2.6.** Negative trends in area, inter-annual rate, and severity of LNS for river basins of the Burdekin Dry Tropics. sd – standard deviation.

**Table 2.7.** Positive trends in area, inter-annual rate, and severity of LNS for river basin of the Burdekin Dry Tropics. sd – standard deviation.

Pivor basin (in	Total area in km <sup>2</sup>		Average LNS in gC m <sup>-</sup>
	and percentage of	Average trend in	<sup>2</sup> year <sup>-1</sup> and as a
decreasing order	those areas with	gC m <sup>-2</sup> year <sup>-1</sup>	percentage of
of area)	positive trends		reference NPP
Upper Burdekin	2.70x10 <sup>5</sup> (27%)	7.6 (sd = 2.7)	-124.5 (-20%)
Belyando	2.50x10 <sup>5</sup> (25%)	6.8 (sd = 3.3)	-151.1 (-31%)
Cape Campaspe	1.53x10 <sup>5</sup> (15%)	7.3 (sd = 3.0)	-113.4 (-21%)
Suttor	1.67x10 <sup>5</sup> (16%)	8.7 (sd = 3.7)	-139.6 (-26%)
Bowen Broken	1.46x10 <sup>5</sup> (14%)	10.1 (sd = 3.6)	-118.4 (-19%)
Bogie			
Lower Burdekin	0.31x10 <sup>5</sup> (3%)	8.6 (sd = 3.4)	-117.2 (-18%)
Entire BDT region	10.16x10 <sup>5</sup> (100%)	7.9 (sd = 3.4)	-130.7 (-23%)

### 2.3.5. Comparison of LNS and environmental characteristics

For the entire BDT, the overall spatial distribution of annual hillslope erosion was

strongly correlated (k = 0.7) with LNS. Other environmental variables indicative of degradation (gully density, rainfall erosivity, and sediment load) were also high overall, (k = 0.6). For individual pixels, maps of correlation revealed strong regional differences (F07). The Suttor had the greatest spatial agreement between LNS and each

environmental variable, while the Bowen Broken Bogie had the least. Strong agreement between annual hillslope erosion and LNS occurred throughout the BDT (Figure 2.7a), particularly in the central Upper Burdekin, Cape Campaspe, Suttor and Belyando. The spatial agreement between LNS and gully density (Figure 2.7b) were largely similar to that of LNS and hillslope erosion except the presence of large clusters of low kappa values in the northern basins. The spatial pattern in kappa values for LNS and rainfall erosivity (Figure 2.7c) and sediment load (Figure 2.7d) resembled rainfall gradients in the region, northeast to southwest.

VAST classes	Average trend in gC m <sup>-2</sup> year <sup>-1</sup>	Average LNS in gC m <sup>-2</sup> year <sup>-1</sup>	Average LNS as a percentage of	
0-'Residual'	0.3 (sd = 4.7)	-110.2 (sd = 63.7)	-19.7% (sd = 11.1)	
1-'Modified'	1.0 (sd = 4.8)	-110.2 (sd = 61.5)	-19.4% (sd = 10.5)	
2-'Transformed'	1.1 (sd = 5.1)	-115.2 (sd = 62.6)	-21.6% (sd = 11.7)	
3-'Replaced'	0.6 (sd = 6.1)	-123.6 (sd = 66.1)	-24.9% (sd = 12.6)	
4-'Removed'	1.5 (sd = 5.3)	-171.5 (sd = 98.2)	-32.7% (sd = 17.7)	
5-'Bare'	-0.9 (sd = 7.3)	-130.2 (sd = 78.6)	-23.9% (sd = 14.5)	

**Table 2.8.** VAST class comparison with inter-annual trends in LNS and average LNS. sd – standard deviation.

### **2.4. Discussion 2.4.1. Land capability classification (LCC) and local NPP scaling (LNS)** The basis of selection of the reference NPP and detection of anthropogenic

reductions in LNS is the classification of the landscape into uniform units (LCCs) with respect to the environmental factors that affect NPP. The procedure was generally successful in creation of classes of environmentally uniform pixels, differing only in the long-term degree of degradation. The same reference sites were frequently selected in multiple, sometimes consecutive, years for the 14 years included in the study and therefore potentially for a longer term. This indicates that degradation, as detected with LNS, corresponded to sites that were persistently below the potential. This emphasized that these sites were not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall. The value of incorporating interannual variation of precipitation in the classification rather than a climatological average is illustrated by the comparison of GLM. UMDLCC proved better able to minimize within-LCC variance while also maximizing the between-LCC variance (Table 2.1, Figure 2.4a & Figure 2.4b). The large numbers of UMD reference sites that fell in the VAST 'residual' class and the larger reductions in NPP in VAST classes with higher levels of human modification, offer further evidence of the reliability of the UMDLCC classification (Table 2.8). Furthermore, the spatial coincidence of differences in management with differences in LNS found by visual inspection of high resolution imagery suggests that the procedure was able to distinguish regional, anthropogenic land degradation from natural variation in environmental factors.

Nevertheless, undetected errors may arise in the classification process, some of which are noted in the Methods section (2.2.1). Changes in land cover during the study period are unlikely to have caused errors since the rates of pasture clearing decreased dramatically throughout the Burdekin region from 1988 to 2002 and remained relatively low during the study period (2000 to 2012, [151]). A more fundamental problem might arise because the classification procedure did not allow for any interactions between environmental factors in different parts of the study area. A possible example of this from the BDT is the location of the largest spatial variations in LNS and its inter-annual trends near the coastline (e.g. Lower Burdekin and Bowen Broken Bogie) where rainfall is highest. This is an example of a drawback of statistical classification which can only

account for additive effects of the environment whereas, for example, moisture availability can alter the response of production to management [152], maybe nonlinearly. This points to an advantage of replacing the statistical derivation of LCCs with a process-based model that can convolve the environmental factors in realistic mechanisms. Such a model run in "potential" mode, which is without any anthropogenic effects, could create a reference NPP for each pixel. At the present time, however, the environmental variables and parameters needed for a useful process model are only rarely available.



Figure 2.7 Similarities between (a) annual hillslope erosion, (b) gully density, (c) rainfall erosivity, and (d) sediment load and percentage LNS as indicated by fuzzy numeric kappa.

# 2.4.2. Extent of degradation of NPP in BDT

Across the entire BDT region, from 2000 to 2013, the average annual reduction in

NPP below the reference was 2.14 MgC  $m^{-2}$  year<sup>-1</sup> (Table 2.2). The average LNS in the

non-degraded class (arbitrarily set at LNS between 0 and -29%) was -97.5 gC m<sup>-2</sup> year<sup>-1</sup>

and the degraded class (LNS <30%) -209.1 gC m<sup>-2</sup> year<sup>-1</sup> (Tables 2.4 & 2.5). However, owing to the greater area of 'non-degraded' land in the entire BDT (80.3%) compared to the 'degraded' class (19.7%) (Table 2.2), the total NPP reduction in non-degraded areas was actually greater. Reductions in NPP, as indicated by low LNS, affect the carbon pool in several ways: by reduced rates of sequestration [153]; by reduction in biomass of live and dead vegetation; by loss of soil organic matter [154-156]; or by a shortened growing season, for example among introduced, less-adapted, pasture species [157,158]. The large reduction in NPP found here is in agreement with reports of episodes of widespread land degradation occurring in the BDT [22,95,159].

Overall, positive temporal trends in LNS were twice as common as negative trends (Tables 2.6 & 2.7). The 'Non-degraded with no trend' class had the largest total area (65.3%). This class was widespread in every river basin, indicating that most of the BDT region was not affected by severe degradation. In other areas, for example in Belyando and Bowen Broken Bogie, the average LNS of 'Degraded with positive trends' areas suggests that significant areas were recovering from earlier degradation (Table 2.7). Nevertheless, some areas were degrading between 2000 and 2013 and in some, their negative trends intensified through the study period, as indicated by the extent of the 'Degraded with negative trends' class (Table 2.2). Areas classified as 'Degraded with negative trends' occupied 24.7% of the entire BDT –candidate areas for actions to reverse or at least arrest the trend. There were a few instances of 'Degraded with no trends', a possible indicator sites in a state of long-term, maybe permanent, irreversible degradation or approaching this state. Permanent degradation is a serious condition since it is generally reversible only with intensive remediation [7,60] which often costs more than

the value of the restored land, however, there were a few areas of 'Degraded with positive trends' which may be examples of land that has been rehabilitated.

# Chapter 3 Degradation of Non-Photosynthetic Vegetation in a Semi-Arid Rangeland

# **3.1. Introduction** Land degradation is the process where undesirable conditions emerge due to human and natural causes [3,39,61]. Global assessments suggest varying severities of degradation in a multitude of climate zones, including in drylands (aridity index < 0.65), where degradation has far-reaching implications [3,6,60,111]. Drylands are important components of the global terrestrial surface: the Millennium Ecosystem Assessment [3] states that drylands cover over 40% of Earth's terrestrial surface, support 50% of the world's livestock, store 46% of global carbon, and contain 38% of the global population, including many who are affected by degradation Various definitions of degradation of drylands, also referred to as desertification, exist both regionally (e.g. Australian rangelands) [16,107] and globally [18,19,111,160]. The United Nations Convention to Combat Desertification (UNCCD [9]) defines desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities". Other definitions make a distinction between short term reductions in productivity related to weather fluctuations (e.g. droughts) and long term reductions that result from excessive utilization of the land with respect to its resilience. Prince [7], for example, states "desertification [degradation] refers to the process by which changed biogeophysical conditions emerge owing to human actions that cannot be supported by the resource base ...... and that will not quickly return to their former, nondesertified conditions, either naturally or by application or minor management practices". This definition serves to distinguish drought, in which vegetation and edaphic factors

fully recover from a temporary reduction in rainfall, and degradation in which there is

complete recovery when rainfall increases. While it is clear that human activity is both directly and indirectly responsible the disruption of important terrestrial process and substantial land cover change, there is little objective of information regarding the extent and severity of human-induced degradation [111].

Monitoring land degradation relies upon the evaluation of differences in land condition between its potential and actual conditions [121]. Thus it is necessary to identify potential, non-degraded, reference standards, preferably with little-to-no management. Various methods have been used including land surveys [127] and visual assessment of imagery. However, these have many limitations [7,63].

Vegetation dynamics have become an important way to describe land condition and its prevailing trends [7,161]. In particular, the use of remotely sensed satellite data has allowed for the monitoring and evaluation of certain important vegetation characteristics, including net primary productivity (NPP) and fractional vegetation cover (FC), through time and space with the capability for applications from local to regional scales [43,162,163]. Fractional cover refers to the surface area covered by vegetative material compared with bare ground, while NPP is the rate at which atmospheric carbon is sequestered through photosynthesis, after autotrophic respiration, and is usually measured in the field as increments in the amount of vegetation matter produced over time, although this inevitably misses biomass shed by senescent components and also consumption by herbivores. The availability of satellite sensors, such as the Moderate Resolution Imaging Spectrometer (MODIS), have allowed for long-term monitoring of vegetation at durations long enough to distinguish degradation from many natural losses of vegetation such as prolonged drought [164]. NPP has been used for monitoring

degradation in numerous drylands including southern Africa [48,64] and in Australian rangelands (Jackson and Prince 2016, in press). However, considerably less is known about the impact of human-induced degradation on other important aspects of vegetation including cover, both photosynthetic and non-photosynthetic, and their complement bare ground.

Vegetation characteristics have been assessed using vegetation indices derived from the remote sensing of spectral reflectance (e.g., [7,165]) of which one of the most widely used is the Normalized Difference Vegetation Index (NDVI), which provides information on the location and density of green vegetation. However, there are other components of degradation that are equally or more important and which cannot be measured directly with NDVI. These include non-photosynthetic components of vegetation (NPV) that include dead plant material, both standing and detached, leaf litter, bark, wood and stems, all of which can protect the soil surface from erosion and some of which provide dry-season fodder for livestock. Another vegetation index, the Cellulose Absorption Index (CAI) [166] was developed to distinguish NPV from bare soil. CAI has been applied in drylands [167], with some quantifying woody biomass (e.g., [168]) and others assessing crop litter (e.g. [169]). The measurement of NPV using CAI, as originally developed, requires high spectral resolution, near infrared, measurements that are not available from any suitable current satellite radiometer [170], hence NPV has not been used widely, and never at regional at regional scales. Nevertheless, NPV is potentially valuable for assessing the impact of degradation on the landscape [167,171]. Furthermore the relationship between persistent, long-term reductions in productivity, owing to human-induced degradation, and vegetation cover dynamics are not well

understood. The understanding of key symptoms of degradation (e.g. soil erosion, evapotranspiration) and its future implications on land surfaces processes (e.g. disruption of the surface energy budget) may be dramatically improved through examination of nonphotosynthetic vegetation across varying severities of degradation.

Guerschman et al. [2] developed a method for linear unmixing fractional cover of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare soil (BS) in Australian drylands using a ratio between shortwave-infrared MODIS bands (2130 and 1640 nm) as a surrogate for CAI, and regressed it with NDVI to unmix NPV from soil and photosynthetic vegetation components in the field of view.

The objective of this study was to evaluate the fractional cover of NPV, along with PV and BS, for degraded and non-degraded conditions using the dataset developed by Guerschman et al. [2]. The region used was the extensive rangelands (>10,000 km<sup>2</sup>) of the Burdekin Dry tropics (BDT) in Queensland, Australia, where Jackson and Prince (2016, in press) used the Local NPP Scaling (LNS) to measure and monitor long-term degradation. In this study, the LNS approach was used to estimate degradation with which to compare the components of fractional cover.

The specific aims were to measure the components of fractional cover to; (1) characterize relationships with NPP, (2) examine variations in fractional cover under degraded and non-degraded conditions, and (3) quantify reductions in NPV, as well as PV and BS, cover and evaluate their ability to characterize degradation.



# 3.2. Materials and Methods 3.2.1. Study area

Figure 3.1 Location of the Burdekin Dry Tropics (BDT) region in the State of Queensland, Australia, the six major river basins (a) and five locations (b-f) identified as degraded in Chapter 2, and major roads and towns.

The Burdekin Dry Tropics (BDT) is a large catchment, covering approximately 7.45x10<sup>6</sup> km<sup>2</sup>, located in north Queensland, Australia. Across the region, the terrain is largely flat with little variation in slope and aspect, although elevation gradually increases inland [113]. Six large river basins are contained in the BDT (Figure 3.1): the Upper Burdekin (2.26x10<sup>6</sup> km<sup>2</sup>), Belyando (2.08 x10<sup>6</sup> km<sup>2</sup>), Cape Campaspe (1.18x10<sup>6</sup> km<sup>2</sup>), Suttor (1.07x10<sup>6</sup> km<sup>2</sup>), Bowen Broken Bogie (0.63x10<sup>6</sup> km<sup>2</sup>) and Lower Burdekin (0.23x10<sup>6</sup> km<sup>2</sup>). There is a steep decreasing gradient in rainfall from the coast inland with average seasonal rainfall varying from 400 to 1500mm. More than 70% of rainfall falls during summer months (December-February), runoff variability is high [117,118], and discharge from rivers and creeks occurs in large pulses associated with intense but brief storms. During the study from 2000 to 2013, years with low (e.g. 2002-2007 & 2013;  $\leq$  500mm year<sup>-1</sup>) and high (e.g. 2000-2001 & 2008-2012;  $\geq$  600mm year<sup>-1</sup>) accumulations occurred (Jackson and Prince 2016, in press).

Regional variations in key environmental factors, such as moisture availability,





fire frequency, and soil properties, are strongly related to the substantial spatiotemporal variation in vegetation type and quantity. Native vegetation varies from dense to sparse forest to shrub-land and open grassland. Approximately 83% of the BDT is savanna consisting of mixed grass and trees, however there are smaller areas that consist exclusively of shrubs (1%), grasses (8%), or rain-fed crops (8%). The croplands, both irrigated and rain-fed, are found in northeastern, higher rainfall areas.

The major land use (85-90% of the BDT) is livestock production, predominately beef cattle, on unimproved pastures [113]. According to the State of Queensland (2011), approximately 12% of the BDT has grazing practices likely to result in degradation.

Five locations were selected throughout the study region (Figure 3.1b-f), where there was evidence of degradation identified by Jackson and Prince (2016, in press) but where there were also clear contrasts between degraded and non-degraded conditions.

### **3.2.2. Fractional Cover**

The MODIS-derived Fractional Cover metrics product [2] was obtained from the AusCover data archive (www.auscover.org.au; accessed 09/01/2015) (note this is not the MOD44A product of the same name). The 8-day fractional cover (FC) product has a 500x500m resolution and covers the entire Australian continent and has been validated with in-situ measurements throughout the BDT [172]. The dataset used MODIS surface reflectance bands to develop a surrogate for CAI and regressed it with NDVI to separate the endmember components of fractional cover (Figure 3.2): photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare soil (BS) cover. Each component of fractional cover is relative to the other components and sum to 100% for each pixel.

The fractional cover dataset was resampled to 250m using nearest-neighbor interpolation for comparison with the scaled NPP map of Jackson and Prince [173]. Each component of fractional cover was averaged from November to May for each of 14 years from 2000 to 2013. Missing, and questionable observations were removed from the analysis. The use of data at a finer scale than its native resolution is obviously not ideal, but unavoidable for study of large areas. The problem is less in the case of meteorological

variables that change gradually across the landscape, for which downscaling is frequently used. But for land surface conditions such as soils and the fractional cover data it is greater. A mitigating factor is the use of nearest-neighbor resampling that preserves actual, original data values. However, the effect is the appearance of spurious resolution of the product. Here the interpretation of the derived products is confined to minimum resolutions of 1 km<sup>2</sup>. There is also the possibility of functional mismatches, such as unnatural combinations of soil and vegetation types, but these cannot be avoided.

Environmental factor	Variable	Spatial resolution	Duration	Source	Citation
	Rainfall				[132]
	Minimum		2000- 2013		
	Temperature				
	Maximum			The	
Meteorological	Temperature			Australian	
(daily)	Water vapor	5km		Bureau of	
(	pressure			Meteorology	[133]
	deficit at 9am				
	Water vapor				
	pressure				
	deficit at 3pm				
	Solar exposure				
	Plant available water holding				
	capacity			ACLEP	[134]
Soil (static)	Soil bulk	1km	Static		
	density				
	Clay				
	percentage				
Vagatation	Foliage				
(1000)	projective	30m	Static	SLATS	[135]
(1999)	cover				

 Table 3.1 Environmental factors used in creating land capability classes (LCCs) in the BDT.

# **3.2.2. Local Scaling of Components of Fractional Cover 3.2.2.1. Land Capability Classes**

Land capability classes (LCCs) are areas that are homogeneous with respect to the

selected environmental factors: meteorology, soil, and vegetation, in this case (Table 3.1).

A k-means [174], unsupervised clustering approach was used to create 14 annual classifications; 50 LCCs for each year from 2000 to 2013. A detailed description of the LCC development and their evaluation is presented in Jackson and Prince [173].

A reference cover, the potential cover for an entire LCC based solely on environmental factors, was obtained from maximum values among all pixels using the frequency distribution of each component of fractional cover for each LCC. The 85<sup>th</sup> percentile was arbitrarily selected as the best estimator of potential cover under the local environmental constraints. Pixels with cover higher than the reference cover were omitted to reduce the effects of anomalous values caused, for example, by small areas such as watering pools that were not used in the creation of LCCs. Masking rivers, open water, roads, settlements, and other human land features not representative of the LCCs also minimized this effect.

### **3.2.2.2. Scaling Approach**

LNS values are the difference between each pixel and its reference within its LCC. Reference values are set to zero and LNS values were therefore zero (equal to the reference cover) or negative (below the reference). Each of the three components of fractional cover were scaled in this way and mapped showing the pixels at their reference and the various LNS values which indicate deficits below the reference. LNS values can be expressed as the percentage of reference cover (scaled value) or as the actual reduction in cover (absolute value). For the sake comparison across LCCs, scaled components of fractional cover (i.e. scaled PV, scaled NPV, and scaled BS cover) refer to the percentage of the reference cover. Finally, for each pixel, the annual results were averaged over 14 years from 2000 to 2013. LNS values calculated using net primary productivity [173] were used to define degradation. Pixels from 0 to -30% LNS were arbitrarily set as non-degraded, and  $\leq$  -31% as degraded.

### **3.2.2.3.** Validation of Scaling Results

Few maps exist that are relevant for comparison with the regional scale studied here. One that does cover the majority of the BDT is the ABCD landscape condition assessment [28], where landscape condition is indicated by descriptive classes: 'A'-good, 'B'-fair, 'C'-poor, and 'D'-very poor; based upon the density of preferred grasses (perennial, palatable, and productive), soil condition, presence of weed species, and woody density [28]. The ABCD condition assessment was based on the Landsat TM derived Ground Cover Index (GCI) from 1996 to 2007 [56] at a 30x30m spatial resolution. GCI is the ratio of ground cover to bare ground. Ground cover was defined as the total organic soil surface cover, including senescent and green grasses and forbs, grass and tree litter and cryptograms, while bare ground included bare soil and rock. Areas with low cover or decreasing cover over the length of the study period or had highly variable cover were assigned to lower classes [175]. Ground, visual validation of the ABCD condition map indicated good overall accuracy (83%) [28], particularly for 'A' and 'D' classes.

The purposes of the LNS and ABCD condition maps differed; ABCD distinguished types of ground cover while LNS measured the proportions of PV, NPV, and BS cover. It should be noted that the ABCD map had important strengths (e.g. multiple characteristics of degradation identified, ground validation) and weakness (e.g. difficulty to transfer approach to other areas, doesn't separate natural effects from management) compared with the LNS map.

For each ABCD condition class, the 14-year average of absolute and scaled components of fractional cover, actual and scaled NPP, and percent degraded were calculated. The 14-year averages were compared to the gradient from 'A' to 'D' condition and to each other.

Spatial agreement between of actual and scaled components of fractional cover, actual and scaled NPP, and the ABCD condition map were examined using Cohen's kappa (k) fuzzy numeric [149]. This elaboration of the simple kappa test includes 'near misses' and allows for coincidences that occur by chance. Values range from 0.0 (change agreement) to 1.0 (perfect agreement) with increasing agreement.

### 3.3. Results 3.3.1. Comparison of Condition Metrics 3.3.1.1. Comparison of Observed and Scaled Components of Fractional Cover and Degradation

Observed and scaled components of fractional cover were substantially different between non-degraded and degraded pixels; scaled PV cover was more than double for degraded than non-degraded, and the proportions of observed and scaled NPV cover remained fairly constant. Observed and scaled BS cover in degraded pixels, however, were higher than non-degraded. In the entire BDT, observed and scaled BS cover were much lower than the other components of fractional cover, especially scaled BS cover.

Fable 3.2 Average of observed components of fractional cover, and their scaled counterparts, in the BDT for pixels
assigned to either degraded or non-degraded NPP classes and for all pixels in the entire BDT. sd = standard
deviation

	Observed cover			Scaled cover		
	PV	NPV	BS	PV	NPV	BS
Non-	38.5%	44.4%	17.6%	-15.2%	-13.8%	-38.3%
degraded	(sd=5.8)	(sd=3.7)	(sd=5.0)	(sd=7.2)	(sd=5.9)	(sd=12.0)
Degraded	29.2%	46.1%	24.2%	-32.1%	-12.3%	-23.4%
	(sd=5.3)	(sd=4.4)	(sd=6.3)	(sd=9.0)	(sd=6.5)	(sd=11.9)
Entire	36.5%	44.8%	19.0%	-18.8%	-13.5%	-35.1%
BDT	(sd=6.8)	(sd=3.9)	(sd=6.0)	(sd=10.3)	(sd=6.1)	(sd=13.4)

### **3.3.1.2. Comparison of Components of Fractional Cover along a Rainfall Gradient** The relationship between rainfall and components of fractional cover were as

expected, with greater observed values in wetter regions, steady declining to the drier end of the gradient (Table 3.3). The scaled values were similar for PV, declining with reducing rainfall but were reverse for NPV with the same decline as PV. BS was unaffected by rainfall.

## **3.3.1.3. Inter-Comparison of NPP and Fractional Cover**

For all pixels in BDT together, scaled components of fractional cover had the strongest correlations with scaled NPP and had larger positive and negative slopes than observed components (Table 4). NPV, and scaled NPV, showed little relationship with scaled NPP; with the lowest slope coefficient and standard deviation of residuals, and weak negative correlation. Only PV, and scaled PV, had positive correlations with scaled NPP. BS, and scaled BS, had moderate, negative correlations with scaled NPP and also had high variations among residuals.

# 3.3.2. Scaled Components of Fractional cover and Scaled NPP 3.3.2.1. Geographic Relationships between Scaled Components of Fractional Cover and Scaled NPP

At the scale of the entire BDT, there was spatial variation in the 14-year mean of scaled components of fractional cover and there were areas with low scaled components

of fractional cover throughout the region, each with its own spatial distribution (Figure 3.3a). In fact, there was regional agreement across the BDT between low scaled components of fractional cover, scaled NPP, and ABCD condition (Figure 3.3a). Scaled PV cover, scaled NPP and ABCD condition had the strongest regional agreement. Scaled BS cover was nearly inverse of scaled PV and scaled NPP. Scaled PV cover was higher in the northern BDT and lower in the southern BDT than either scaled NPV or scaled BS cover. There were no clear spatial relationships between scaled NPV cover and other scaled components of fractional cover.

Annual	Number	Ob	served cov	ver	Scaled cover				
rainfall	of pixels	PV	NPV	BS	PV	NPV	BS		
(mm)									
1700-	1715	53.0%	36.3%	13.5%	-10.5%	-23.2%	-46.4%		
2000		(sd=5.8)	(sd=3.4)	(sd=3.9)	(sd=7.3)	(sd=6.6)	(sd=11.3)		
1400-	6024	50.1%	39.5%	13.4%	-12.4%	-17.9%	-47.6%		
1699		(sd=5.9)	(sd=3.7)	(sd=4.2)	(sd=8.0)	(sd=6.6)	(sd=11.6)		
1100-	19507	48.2%	40.7%	14.1%	-12.5%	-16.8%	-45.5%		
1399		(sd=5.0)	(sd=3.3)	(sd=4.1)	(sd=7.6)	(sd=5.8)	(sd=10.7)		
800-	111549	44.4%	43.0%	15.1%	-13.4%	-14.0%	-41.5%		
1099		(sd=5.2)	(sd=3.8)	(sd=4.4)	(sd=7.8)	(sd=6.1)	(sd=12.1)		
500-	1558842	35.7%	45.0%	19.3%	-19.3%	-13.4%	-34.5%		
799		(sd=6.3)	(sd=3.8)	(sd=5.9)	(sd=10.3)	(sd=6.0)	(sd=13.3)		

Table 3.3 Components of fractional cover along a gradient of average annual rainfall. sd – standard deviation

Table 3.4 Regression of scaled net primary productivity (scaled NPP; from Jackson and Prince 2016, in press) with components of fractional cover; photosynthetic vegetation (PV) cover, non-photosynthetic vegetation (NPV) cover, and bare soil (BS) cover and their scaled counterparts. Significance of correlation coefficient (r): for n > 2000, r >0.19 is significant at the  $p \le 0.05$ ; r >0.25 at  $p \le 0.01$ ; r >0.32 at  $p \le 0.001$ .

<b>Regression with scaled NPP</b>	<b>Observed cover</b>			Scaled cover		
	PV	NPV	BS	PV	NPV	BS
Slope coefficient	0.06	-0.01	-0.04	0.13	-0.02	-0.11
SD of residuals	5.8	3.8	5.5	6.2	5.9	11.5
r	0.53	-0.22	-0.40	0.80	-0.21	-0.51


Figure 3.3 Comparison of the individual scaled components of fractional cover averaged from 2000 to 2013 (a) for the entire BDT from Nov to Apr showing, scaled photosynthetic vegetation (PV), scaled non-photosynthetic vegetation (NPV), scaled bare soil (BS) cover, a composite of scaled fractional cover components, scaled NPP, and Karfs et al. [28]'s ABCD land condition assessment from with (b) fine scale comparisons of the five locations shown in (a) and a true color composite of Landsat imagery. Grey lines in (a) are basin boundaries and in (b-f) are property boundaries.

Each river basin had large areas of high and low scaled PV, NPV, and BS cover,

as shown by the scaled fractional cover composite (Figure 3.3a: Scaled FC composite).

There was a clear gradient of ABCD condition from 'A' in the north to 'D' in the south.

Southern portions of the BDT, including parts of the Belyando, Cape, and Suttor, had the majority of pixels classified in the 'C' or 'D' class.

At a finer spatial scale still, there were distinct differences in scaled fractional cover composition and gradients from high to low scaled PV, scaled NPV, and scaled BS cover were clear (Figure 3.3b-f). Sharp contrasts in the scaled components of fractional cover occurred both within and between properties. There were also abrupt differences in scaled PV and scaled BS cover along property boundaries (Figure 3.3c-f: scaled PV cover & scaled BS cover) and the scaled fractional cover composite (Figure 3.3c-f: scaled FC composite) as shown in the sharp contrast between high scaled PV to high scaled NPV and scaled BS cover for pixels at property fences. In some cases, there were abrupt differences for only one or two scaled components of fractional cover, while others had no obvious difference between properties (e.g. Figure 3.3b: scaled PV cover & Figure 3.3f: scaled NPV cover).

Table 3.5 Comparison of kappa values for maps of seasonal components of fractional cover, seasonal NPP, scaled
components of fractional cover, scaled NPP, and the Karfs et al. ([28]) ABCD condition in the Burdekin Dry Tropics.
Comparisons were made with the fuzzy kappa statistic [150] applied to each pair of maps taken as a whole, hence
the single value for each pair

	DV	NDV	BC	NDD	Scaled	Scaled	Scaled	Scaled	ABCD
	IV	INI V	<b>D</b> 3		PV	NPV	BS	NPP	condition
PV	Х	0.59	0.52	0.92	0.46	0.63	0.49	0.54	0.58
NPV	-	Х	0.62	0.59	0.67	0.45	0.57	0.68	0.67
BS	-	-	Х	0.53	0.73	0.66	0.81	0.72	0.78
NPP	-	-	-	Х	0.48	0.64	0.51	0.54	0.58
Scaled PV	-	-	-	-	Х	0.58	0.79	0.75	0.68
Scaled NPV	-	-	-	-	-	X	0.71	0.55	0.63
Scaled BS	-	-	-	-	-	-	Х	0.69	0.70
Scaled NPP	-	-	-	-	-	-	-	Х	0.73
ABCD condition	-	-	-	-	-	_	-	-	Х

At spatial scales relevant to most degradation analyses, there were numerous examples of variation of scaled components of fractional cover spatially related to property boundaries (Figure 3.3b-f). Low scaled NPP was strongly related with high scaled BS cover and low scaled PV cover (e.g. Figure 3.3c & e). Similarly, the spatial patterns of 'C' and 'D' classes (the most degraded classes) were also strongly related to areas where scaled BS cover was much higher than scaled PV and scaled NPV cover (e.g. Figure 3.3d). However, the relationship between scaled NPV cover and either scaled NPP or 'C' or 'D' classes were less clear.

Areas classified as 'D' often corresponded to high scaled BS cover (e.g. -5%), low scaled PV cover (e.g. -20%) and medium scaled NPV cover (e.g. -15%). For the 'C' class, a more diverse mixture of scaled components of fractional cover was found, including high scaled BS cover and medium to low scaled PV and scaled NPV cover. There were abrupt differences in scaled components of fractional cover, scaled NPP, and ABCD condition assessment were found along property boundaries throughout the BDT (Figure 3.3b-f). Sudden shifts in scaled PV and scaled BS cover were found around boundaries in each inset. Scaled NPV cover experienced sudden shifts as well, although scaled NPV had inconsistent spatial co-variation with scaled PV and scaled BS cover. Gradients from high-to-low scaled NPP were visually similar to transitions from 'B' to 'D' classes (e.g. Figure 3.3c & 3.3d). Frequently, pixels with high scaled NPP (0 to -100 gC m<sup>-2</sup> yr<sup>-1</sup>), corresponded to 'A' or 'B' classes, high scaled PV cover and low scaled BS cover.

# **3.3.2.2.** Spatial Similarities of Scaled Components of Fractional Cover and Scaled NPP

There was almost perfect agreement between PV and NPP (Table 3.5) and substantial agreement between scaled PV and scaled NPP. While NPV had near identical agreement with PV and BS, scaled NPV had greater agreement with scaled BS than scaled PV. Observed components of fractional cover had poor agreement with their scaled counterparts, however BS and scaled BS had substantial agreement. In addition, BS and scaled BS, had better agreement with observed, and scaled, components of fractional cover and NPP. The ABCD map had similar agreement with all scaled components of fractional cover and scaled NPP. Scaled NPP had near identical agreement with scaled PV and scaled BS but the poorest agreement with scaled NPV.

Table 3.6 Comparison of ABCD condition, from Karfs et al. [28], with scaled NPP and scaled fractional cover for the entire BDT region.

ABCD	Obs	served	cover	Sca	aled cov	ed cover Scaled			Perc	
conditio n classes	r of Pixels	PV	NPV	BS	PV	NPV	BS	NPP (gC m <sup>-2</sup> yr <sup>-</sup> <sup>1</sup> )	ent scale d NPP (%)	enta ge degr aded (%)
ʻA'- Good	148749	40.7	45.5	14.8	-15.8	-11.4	-41.7	-113.3	-18.2	8.2
ʻB'- Fair	410413	37.2	45.6	17.7	-17.9	-12.6	-37.5	-115.0	-20.2	15.2
'C' - Poor	454806	33.4	45.2	21.4	-21.3	-13.9	-31.5	-126.7	-24.3	27.2
'D' - Very Poor	139554	29.4	44.2	26.3	-28.1	-15.6	-23.0	-162.1	-33.0	55.8



Figure 3.4 The percentage of degraded pixels across a gradient of low-to-high scaled components of fractional cover: scaled photosynthetic vegetation (scaled PV), scaled non-photosynthetic vegetation (scaled NPV), and scaled bare soil (scaled BS) cover.

#### **3.3.2.3.** Comparison of Degradation Maps

ABCD condition classes had good agreement with scaled NPP and percent-scaled NPP, and both decreased as land condition worsened from 'A'-to-'D' (Table 3.6). Nearly 56% of the 'D' class, and 27% of the 'C' class, were degraded. Similar to scaled NPP, both scaled PV and scaled NPV cover decreased as ABCD condition classes worsened, although scaled PV cover decreased more rapidly between classes. Scaled NPV cover,

much like NPV cover, remained fairly constant. Scaled BS cover, however, increased as ABCD condition worsened.

There were trends in components of fractional cover across ABCD conditions. In the 'A' class nearly equal amounts of PV and NPV cover were present, while in the 'D' class there were nearly equal amounts PV and BS cover. This indicated PV cover decreased from 'A' to 'D', BS cover increased, and NPV cover remained the same.

There were three different relationships at the intersection of scaled components of fractional cover and degraded pixels (Figure 3.4). The number of degraded pixels decreased as scaled PV cover increased and the relationship was strongest between -15% and -5%. The number of degraded pixels increased for both scaled NPV cover and scaled BS cover, however each had different relationships. As expected, scaled BS increased gradually with more degraded pixels. Scaled NPV cover, however, had no a weak correlation with the number of degraded pixels and remained fairly constant at intermediate scaled NPV values (i.e. -7 - -18% cover). Interestingly, all scaled components of fractional cover had equal amounts of degraded pixels when their scaled values were -8% cover.

#### **3.3.3. Relationships between Components of Fractional Cover and Degradation** There were clear differences found between the degraded and non-degraded

pixels for the three components of fractional cover (Table 3.7). PV and NPV had a weakened correlation (both observed and scaled cover) for degraded pixels compared with non-degraded. Conversely, the degraded and non-degraded relationship between NPV and BS, was stronger for degraded pixels. PV and BS had the strongest correlation and slope coefficients for both observed and scaled components of fractional cover.

#### **3.3.3.1.** Comparison of Inter-Annual Trends

There was spatial variation for inter-annual trends of scaled components of

fractional cover in the entire BDT, although there were overlapping areas of negative trends for each (Figure 3.5a). In many cases, there were large areas of positive and negative inter-annual trends. Visually, inter-annual trends in scaled PV cover were

decidedly similar to scaled NPP.

Table 3.7 Slope and correlation coefficients and standard deviation of residuals from linear regression between each component of fractional cover; photosynthetic vegetation (PV) cover, non-photosynthetic vegetation (NPV) cover, and bare soil (BS) cover identified as degraded and non-degraded by scaled NPP. Scaled components of fractional cover are also presented. See Table 2 for the significance of correlation coefficients (r).

		O	bserved co	over	S	caled cove	er
		PV &	PV &	NPV &	PV &	PV &	NPV &
		NPV	BS	BS	NPV	BS	BS
Non-	Slope	-0.7	-0.8	-0.2	-0.4	-0.4	-0.2
degraded	Coefficient						
	SD of	5.5	4.7	3.8	7.2	6.2	5.9
	residuals						
	r	-0.5	-0.6	-0.2	-0.3	-0.6	-0.4
Degraded	Slope	-0.1	-0.6	-0.4	-0.0	-0.6	-1.1
	Coefficient						
	SD of	5.2	3.6	3.6	6.5	10.4	9.4
	residuals						
	r	-0.1	-0.7	-0.6	-0.0	-0.5	-0.6

There were also differences in the inter-annual trends in scaled components of fractional cover across property boundaries (Figure 3.5b-f). In some cases, there were different trends of scaled components of fractional cover along boundaries (e.g. Figure 3.5b &d-e). In other cases, trends were not related to boundaries (e.g. Figure 3.5f). Nevertheless, there were also cases where few trends were present (Figure 3.5c), despite prior evidence of degradation (Figure 3.3c).

There were numerous examples of inter-annual trends scaled components of fractional cover where negative trends of one scaled component were complemented by

positive trends of another scaled component. For example, positive trends of scaled PV cover were located in areas that corresponded to negative trends of scaled BS cover (Figure 3.5f). Similarly, negative trends of scaled NPV cover corresponded to positive trends of scaled BS cover (Figure 3.5e). Negative trends of scaled PV and scaled NPV cover corresponded to positive trends of scaled BS cover (Figure 3.5e).

There was near perfect agreement for all significant inter-annual trends of scaled components of fractional cover and scaled NPP, particularly between trends of scaled PV cover and trends of scaled NPP (Table 3.8) as shown in (Figure 3.5a). Trends of scaled NPV cover were more similar to trends of scaled PV cover than with trends of scaled BS cover. For all comparisons, the spatial agreement with trends of scaled BS cover was the lowest.



Figure 3.5 Comparison of inter-annual trends of individual scaled components of fractional cover and scaled NPP from 2000 to 2013 (a) for the entire BDT from Nov to Apr showing, scaled photosynthetic vegetation (PV), scaled non-photosynthetic vegetation (NPV), scaled bare soil (BS) cover, scaled NPP with fine scale comparisons of the five locations shown in (a) and a true color composite of Landsat imagery. Grey lines in (a) are basin boundaries and in (b-f) are property boundaries.

3.3.4. Inter-Annual Trends in Scaled Components of Fractional Cover

There were different relationships between negative inter-annual trends of scaled NPP and scaled components of fractional cover (Figure 3.6). Slopes of scaled PV cover had the clearest relationship with negative trends of scaled NPP. Slopes of scaled NPV and slopes of scaled BS cover had not clear relationship with negative trends of scaled NPP, although, unexpectedly slopes of scaled NPV cover had a stronger relationship than slopes of scaled BS cover.

Table 3.8 Comparison of kappa values for maps of inter-annual trends in scaled components of fractional cover and inter-annual trends in scaled NPP in the Burdekin Dry Tropics. Comparisons were made with the fuzzy kappa statistic [150] applied to each pair of maps taken as a whole, hence the single value for each pair.

	Trends of scaled PV	Trends of scaled NPV	Trends of scaled BS	Trends of scaled NPP
Trends of scaled PV cover	Х	0.86	0.82	0.93
Trends of scaled NPV cover	-	Х	0.82	0.85
Trends of scaled BS cover	-	-	Х	0.82
Trends of scaled NPP	-	-	-	Х

#### **3.3.4.1.** Comparison with Vegetation, Assets, States, and Transitions (VAST)

strong agreement with increasing vegetation modification; trends of PV cover increased, while trends of BS cover decreased (Table 3.9). The inter-annual trends of scaled NPV cover had no clear relationship with the VAST classification and two VAST classes had negative trends while the others were positive. VAST's 1-'modified' class had smaller slope coefficients than expected given the slopes for 0-'residual' and 2-'transformed' classes.

In the entire BDT, inter-annual trends for scaled PV and scaled BS cover had



Figure 3.6 Plot displays the relationship between the inter-annual slope of scaled fractional cover and the proportion of significant, negative trends of scaled NPP, for each component of fractional cover: photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare soil (BS).

#### **3.4. Discussion 3.4.1. Relationship between Components of Fractional Cover and NPP** Three components of fractional cover were compared with existing metrics of

land condition to evaluate their ability to discriminate regional patterns of degradation. A key difficulty in comparing different measurements of degradation is the interpretation of each. In this study, each component of fractional cover was individually compared with NPP. Since PV is the photosynthetic component of vegetation Guerschman et al.'s [2] unmixing of total cover, it was not surprising that PV cover and NPP, and their scaled transforms (i.e. scaled PV cover and scaled NPP), were strongly correlated (r=0.80; Table 3.4) and had near identical spatial patterns (k=0.9, Table 3.5). Differences in PV cover and NPP can be expected since the calibration of PV in Australian rangelands [172] involved the principal component of NPP [176]. In fact, some have reported PV to be superior to NDVI in remotely sensed calculations of vegetation productivity [177], despite the near linear relationship between NPP and NDVI in drylands [7].

Likewise, variation in BS cover was moderately, but negatively related to NPP (r= -0.5, Table 3.4) and between scaled BS cover and scaled NPP (k=0.7 for both, Table 3.5). The aim of vegetation indices is to distinguish vegetation from bare ground and therefore the lack of vegetation, and high BS cover, is easily detected using such indices. The negative correlation between BS and PV was not as strong as anticipated, probably due to inaccuracies in differentiation of NPV and BS.

NPP is the process by which biomass is created, both currently live (PV) and dead (NPV) and thus observations of NPV should be related to PV and NPP. However, degradation may result in loss of NPV through various processes including wind erosion and fire. In fact, in the BDT, the relationship between NPP and NPV was unclear, as shown in the non-significant, negative correlation with NPV (r=-0.2 with p=0.10, Table 3.4), and NPV remained constant compared to a gradient of scaled NPP (Figure 3a). Alternative measures of productivity, such as net ecosystem productivity (NEP) and net biome production (NBP), may be better related to NPV, since they include NPP accumulated prior to the time of measurement and also because NPP measures total production (above and below ground) unlike surface cover.

VAST alassas	Scaled slopes					
VAST Classes	PV	NPV	BS			
0-'residual'	0.03	0.06	0.66			
	(sd=0.45)	(sd=0.38)	(sd=1.07)			
1-'modified'	0.02	-0.04	0.30			
	(sd=0.30)	(sd=0.32)	(sd=0.81)			
2-'transformed'	0.08	0.04	0.32			
	(sd=0.27)	(sd=0.31)	(sd=0.84)			
3-'replaced'	0.09	0.04	0.28			
	(sd=0.30)	(sd=0.33)	(sd=0.75)			
4-'removed'	0.10	0.10	0.23			
	(sd=0.36)	(sd=0.38)	(sd=0.63)			
5-'bare'	0.23	-0.11	0.22			
	(sd=0.55)	(sd=0.23)	(sd=0.38)			

Table 3.9 Vegetation Assets, States and Transitions (VAST) classification comparison with inter-annual trends for scaled components of fractional cover. sd – standard deviation.

#### **3.4.2. Degradation and Components of Fractional Cover in the BDT** Scaled PV cover from 2000-2013 across the BDT was on average, 32.1% below

the reference for degraded pixels (Table 3.5). The effect of degradation on PV cover was clear; a reduction in PV cover of 11.3% (Table 3.7) and 17% for scaled PV cover (Table 3.2). PV cover, while not the only component of vegetation cover, is closely related to previous interpretations of vegetation cover loss in degradation studies [65] and as was shown by the moderate agreement between scaled PV cover and the ABCD condition map [28] (k=0.6, Table 3.5). Furthermore, in other Australian rangelands, between 10-30% reductions in vegetation cover have been reported [22,153]. Scaled BS cover was on average 35.1% below the reference (Table 3.2), representing a decrease in BS cover but also an increase in PV cover and NPV cover, and an increase in total ground cover (i.e. sum of PV cover and NPV cover).

A key difficulty in comparing degradation, such as reductions in vegetation cover or productivity, with existing studies is the difference in its quantification [7]. For example, existing studies typically report the spatial extent of reductions [178], often

using a arbitrarily determined threshold that represents substantial change, rather than severity of change. This creates a challenge when comparisons are needed between the spatial extent of degradation and the severity of degradation [179]. There is, however, often a complementary relationship between degradation extent and its severity [130]. In the BDT and throughout the State of Queensland, there was extensive clearance of vegetation during the 2<sup>nd</sup> half of the 20<sup>th</sup> century [180] and 80% of all vegetation change in Australia has been attributed to the State from 1981 to 2000 [181], leading to its designation as a global deforestation hotspot [182]. Approximately 28% of inland dry tropics in Queensland have been cleared, and the remainder is mostly in small, isolated fragments [183]. In the more heavily populated, eastern part of the BDT, 22% of the remaining native vegetation was cleared between 1982 and 1990 [184] and 34% was cleared from the coastal southeast inland between 1974 and 1989 [185] – all prior to the study period. The situation in tropical regions of Queensland (where the BDT is located) may be more severe, since approximately 50% of primary forests have been disturbed and degraded since European colonization [186,187], much of it for agriculture and livestock production [188]. It is unclear, however, if enforcement of clearing restrictions since the mid-2000s has reversed the deterioration of PV and NPV cover.

Sites where scaled NPP was degraded and/or deteriorating were of particular interest for their relationship to components of fractional cover. There were conflicting relationships for scaled NPV and the inter-annual trends in scaled NPV cover, with scaled NPP. While there was little spatial relationship between NPV and scaled NPV, with scaled NPP (Figure 3.4), there was a limited relationship with negative trends of scaled NPP (Figure 3.6). Overall there were clear differences between non-degraded and

74

degraded conditions for average reductions in scaled PV and scaled BS cover (Table 3.2) and the inter-relationship between components of fractional cover (Table 3.7). NPV at degraded and non-degraded pixels had little variation at the coarse scale of the entire BDT (Table 3.2, Figure 3.4), however at finer scales, there was evidence of management where NPV varied spatially (Figure 3.3b-f). Furthermore, the effect of degradation on scaled components of fractional cover was detected at both in the entire BDT and at finer spatial scales (Figure 3.4), both weakening (i.e. between scaled PV and scaled NPV cover) and strengthening (i.e. between scaled NPV and scaled BS cover) the correlation between scaled components of fractional cover.

While reductions in NPP give some indication of land condition and possible humaninduced degradation [47], the severity of reductions of fractional cover (i.e. scaled PV, scaled NPV, scaled BS) adds different types of information. Furthermore, the interactions between scaled components provide additional information regarding the characteristics of degradation. For example, the combination of low scaled PV cover and low scaled NPV cover corresponded to areas with high bare ground cover, thus reductions in vegetation production, increased surface albedo, and increased susceptibility to erosion processes. The effect of increased surface albedo and accelerated erosion, however, is obviously less when scaled NPV cover is high, even if scaled PV cover is low. In this instance high scaled NPV may indicate additional dry season fodder for livestock, albeit less nutrient rich than the green, PV components. On the other hand, when NPV and scaled NPV are high and are not fully consumed during the wet season, excess NPV serves as dry season fuel and thus increases the susceptibility to fire on the landscape.

75

Frequent, unmanaged fires may result in the colonization of undesirable species on burncleared pasture and induce long term degradation.

A limitation in many degradation assessments is the lack of proper validation [121]. While the VAST and ABCD condition maps were not intended to represent all aspects of degradation, the substantial agreement with the components of fractional cover and NPP provides some confidence in the present conclusions (Table 3.6). The ABCD condition map is a synthesis of multiple land characteristics (e.g. species composition, erosion susceptibility, exposed bare ground) and it is therefore difficult to separate individual components. Also, the VAST classification was not intended to represent current land deterioration. There were, however, clear relationships between the inter-annual trends of scaled components of fractional cover reported here and VAST classes (Table 3.9). In spite of these limitations, the agreement between the present results and both ABCD and VAST, provides confidence that many characteristics of degradation were effectively monitored in the present study.

#### **3.4.3.** Interpretations of Non-photosynthetic vegetation

Another complication in comparison of components of fractional cover with existing metrics of degradation is the meaning of NPV cover. In some cases separate elements of NPV cover (e.g. standing live material, standing senescent material, or litter) are distinguished, but not in the Guerschman et al. [2] data product. This may explain the weak relationship between NPV cover and scaled NPP (Table 3.4) and PV cover (Table 3.7). Although the presence of senescent NPV cover would be expected to be related to NPP and PV cover, NPV includes woody vegetation that may have little-to-no relationship to current PV cover. The only moderate agreement between NPV cover and PV cover and PV cover (k=0.5; Table 3.5) and NPV cover and BS cover (k=0.6; Table 3.5) may be a

result of these different components of NPV. Interestingly, while NPV was more closely spatially related to BS cover than PV cover (Table 3.5), NPV had similar inter-annual trends most similar to PV cover (Table 3.8) and the percentage of deteriorating (i.e. significant, negative) NPP trends per inter-annual scaled NPV trend (Figure 3.6).

Although scaled components of fractional cover and scaled NPP were useful for monitoring some characteristics of degradation, other characteristics remain difficult to detect. An additional important characteristic, for example, is unfavorable changes in pasture species composition including the encroachment of unpalatable and thus less desirable species [60]; for example, the widespread proliferation of invasive grass and shrub species in parts of the region [189], particularly in the northern BDT [190-192]. This type of degradation has serious consequences for the beef industry, (e.g. [21,57]). It may be that future techniques will be better able to detect transitions in species composition.

It is reasonable to expect variation among elements of NPV within LCCs, for example foliage projective cover for the year 2000, also contributing to weak correlations between scaled NPV with scaled PV (r=-0.30, Table 3.7), and scaled NPV with scaled PV (r=-0.36, Table 3.7).

#### **3.5.** Conclusions

The primary objective of this study was to determine the utility of vegetation fractional cover to characterize instances of human-induced degradation across a dryland landscape. The availability of measurements of fractional cover at regional scales provides an opportunity to explore hitherto unexplored aspects of degradation. Specifically, NPV was examined under non-degraded and degraded conditions as well as in areas with significant evidence of ongoing land deterioration. The fraction of vegetation cover that was identified as NPV represented elements of vegetation (e.g. bark, stems, and leaf litter) often missed in current assessments of vegetation condition and change. Particularly interesting were the spatiotemporal dynamics of non-photosynthetic vegetation and their relationship with NPP. NPV cover was more closely related to temporal, compared to spatial variation, of NPP; providing evidence of long term vegetation decline where degradation processes were ongoing. Spatial variation in NPV proved to be valuable in advancing the understanding of the symptoms of degradation. While there was no spatial relationship between NPV and degradation across the entire study area, investigation of non-degraded and degraded areas within and between property boundaries revealed abrupt differences in NPV, as well as PV and BS.

To some extent, high NPV cover may mitigate the most severe symptoms of degradation. The results suggest that degradation can be assessed, not only in terms of its extent, trend and severity, but also in the NPV, particularly reductions which are related to increased albedo, increased land surface temperature, increased surface evaporation and accelerated erosion, while higher values would indicate additional cattle dry season fodder but also increased susceptibility to fire. It is clear that there were areas with near identical severities and/or rates of degradation but where the symptoms of degradation varied dramatically. Although assessments of the extent and severity of human-induced degradation remain an important component of terrestrial vegetation monitoring, the ability to attribute degradation to specific surface processes improves current assessments of land condition while also informing future risk assessments.

Initiatives aimed at arresting and/or remediating human-induced degradation, such as the Zero Net Land Degradation (ZNLD; [193]), have been developed in response

78

to the uncertainty regarding current estimates of the extent, severity, and symptoms of degradation and the prospect of continuing land deterioration. Specifically, ZNLD seeks to slow current rates of degradation such that local rates of land rehabilitation are at least equivalent to local rates land deterioration [122]. While some have questioned the feasibility of global land degradation neutrality [194], an approach which prioritizes mitigation efforts on regions at risk of the most severe symptoms of degradation based upon NPV cover will accelerate neutrality efforts through the prevention of irreversible degradation[7].

## Chapter 4 Degradation: combined remote sensing and numerical simulation 4.1. Introduction

Land degradation is the deleterious process by which unfavorable conditions (e.g. low agricultural yield, erosion, etc.) emerge, and may ultimately persist, due to combined human and natural causes [3,39,49,61]. While many assessments have reported extensive dryland degradation worldwide [54], there are numerous conflicting reports regarding their location, extent, the biophysical processes involved and their severity that underscore the current uncertainty associated with degradation [7]. In drylands, areas where the aridity index is less than 0.65, degradation may have particularly troubling effects [3,6,60,111] if, as reported by some, it is irreversible. Such degradation reduces in livestock production [195] and also has off-site effects, including sediment transport [196,197], atmospheric dust production [198] and, in extreme cases, detectable changes in climate [199,200]. Globally, drylands support half of the world's livestock, store nearly half of the global terrestrial carbon stock, and are home to 38% of the world's population [3]. Furthermore, the vulnerability of drylands to dramatic, and rapid, fluctuations in environmental conditions underscores their importance in forecasting the effects of impending climate change [199].

Numerous definitions of degradation exist, many of which are subjective and difficult to measure beyond small areas, yet the designation is often applied regionally (e.g. Australian rangelands [16,107]) and globally [17-19,111]. The United Nations Convention to Combat Desertification (UNCCD; [17]) defines desertification as "land degradation in arid, semi-arid and dry sub-humid areas due to various factors including climatic variations and human activities". However, this definition fails to differentiate between short term reductions in productive capacity due to weather fluctuations (e.g.

droughts or heat spells), and long term reductions that result from excessive utilization of the land with respect to its resilience [7,121]. Some commentators incorporate this distinction in their definition of degradation; "the process by which changed biogeophysical conditions emerge owing to human actions that cannot be supported by the resource base and that will not quickly return to their former, non-degraded conditions, either naturally or by application of minor management practices" [7]. This definition acknowledges the distinction between drought, from which vegetation fully recovers after adequate rainfall returns, and degradation, where reductions in productive capacity persist despite the return of favorable environmental conditions.

Since "degradation" is intrinsically a relative statement – degraded from some former non-degraded condition – the identification and monitoring of land degradation logically requires non-degraded, reference standards that have the same potential production for comparison. Prince [121] reviewed four approaches for identifying reference standards: modeling, time-series analysis, spatial comparisons and expert opinion. The most frequently used method is expert opinion - that entails subjective assessments that, like all qualitative methods, cannot be repeated elsewhere and later, nor can they easily be compared with assessments performed by different experts.

Vegetation conditions are the primary indicator of land degradation used in semiarid regions [48,64,201,202], although soil properties and erosion risk can also serve as indicators [40,153]. The vegetation characteristics most widely applied in degradation studies are biomass and net primary productivity (NPP). NPP refers to the rate of carbon fixed into organic material per unit area time into both above and below-ground biomass, while biomass is the combined mass of all living and dead organic matter. The major

81

components of biomass in semi-arid rangeland systems are live (above and belowground) plants and standing dead vegetation. The common use of NPP and biomass since the mid-1980s is due, in part, to the availability of remote sensing data and techniques. The most common of which are various applications of vegetation indices and also surface reflectance measured in several different wavelengths that can map and monitoring land cover. There are others, such as albedo differences, thermal inertia, and surface roughness [106,203,204].

While annual differences in biomass have been thoroughly investigated in relation to degradation [201,202,205], intra-annual variations have not. Acquiring remotely sensed observations during the periods of vegetation green-up and maturity is inhibited by low temporal repeat of measurements and persistent cloud cover. Some have attempted to avoid this limitation by using dry season characteristics to monitor vegetation [93,105]. Nevertheless, a persisting limitation is characterizing the dynamics of degradation during drought and non-drought years. Consecutive years of drought, either observed or simulated using sophisticated mechanistic modeling, are needed to investigate these dynamics of degradation.

More recently some models that use mathematical simulation of productivity and biomass have emerged. Various mechanistic models have proven useful in the investigation of different aspects of degradation [100,206]. The usefulness of many models is constrained, however, by difficulties in simulation of some processes such as evapotranspiration [207-210] and the spatial pattern of vegetation [16,211], which can be a critical aspect of degradation [16,57,62,212]. The greatest constraint, however, is the need for numerous parameters for the modeled process steps and difficulty in calibration

82

and validation. Some models, however, have successfully addressed these problems, generally by extensive parameterization and the availability of regional-scale data for validation.

One model that has addressed these constraints is the AussieGRASS Environmental Calculator [109], which is widely used at a regional scale across the continent of Australia [106,213-215]. The current study aims to explore the properties of degraded land using simulations with the AussieGRASS model. AussieGRASS simulations of live and dead biomass were compared to data from a study done by Jackson and Prince [173], in which Australian rangeland potential productivity and human-induced vegetation degradation were estimated based on environmental data and remotely sensed observations of vegetation production.

Specifically, this study: (1) compared potential productivity in both drought and non-drought years using remotely sensed data and model simulations; (2) related degradation severity to biomass accumulation; and (3) monitored the expression of degradation, in terms of reduction in biomass accumulations, under varied drought conditions.



Figure 4.1 Rainfall variation in the Burdekin Dry Tropics region in Queensland, Australia. Note: Rainfall from both drought years (i.e. 2004 to 2007) and non-drought years (i.e. 2008 to 2011) was investigated (symbolized with colored bars). Dashed line represents 8-year average.

## 4.2.1.1. Burdekin Dry Tropics (BDT) Region The Burdekin Dry

Tropics (BDT) catchment, covers approximately 7.45x10<sup>6</sup> km<sup>2</sup>, located in north Queensland, Australia. The terrain is largely flat with little variation in slope and aspect, although mean elevation gradually increases inland [113]. The average seasonal rainfall varies from 400 to 1500mm increasing from the

coast inland. More than 70% of rainfall occurs during summer months (December-February), runoff variability is high [117,118], and discharge from rivers and creeks occurs in large pulses during intense but brief storms. From 2004 to 2007 there was a drought when rainfall was below 500 mm yr<sup>-1</sup>, while from 2008 to 2011 (Figure 4.1) rainfall increased to at least 600 mm yr<sup>-1</sup> [173].

#### 4.2.1.2. Spyglass Beef Research Station

The Spyglass and Lucky Break properties (Figure 4.2), cover 38,221 hectares in the Charters Towers district of North Queensland. The current study (2004-2011; Figure 4.1) was undertaken prior to its 2012 acquisition by the Australian government for rangeland research.

#### 4.2.1.3. Land use and land cover dynamics

Native vegetation varies from dense to sparse forest, shrub-land and open grassland. Approximately 83% of the BDT, and nearly all of the Spyglass research station, is savanna consisting of mixed grass and trees with interspersed smaller areas consisting exclusively of shrubs (1% in BDT), grasses (8%), or rain-fed crops (8%). Regional variations in key environmental factors, such as moisture availability, fire frequency, and soil properties, are strongly related to the substantial variation in vegetation type and quantity. Small areas of cropland, both irrigated and rain-fed, are in the northeastern, higher rainfall areas.

The majority of land (85-90% of the BDT) is used for livestock production, predominately beef cattle, on unimproved pastures [113]. According to the State of Queensland [216], approximately 12% of the BDT has grazing practices likely to result in degradation.



#### 4.2.2. AussieGRASS Environmental Calculator

The AussieGRASS Environmental Calculator [109] is a continental-scale spatial implementation of the GRASP daily time-step pasture production and water balance model [217]. Environmental factors affecting vegetation biomass are coupled with management (e.g. stocking rate, burning) to simulate pasture growth, biomass accumulation, decomposition, and landscape characteristics (Figure 4.3). The simulations are driven with daily interpolated climate data from SILO [218] and calibrated using satellite data and pasture biomass observations [219]. AussieGRASS outputs were provided as monthly sums and gridded to 5x5km spatial resolution (www.longpaddock.qld.gov.au). Available outputs were pasture growth, total biomass, percent dead, grassfire risk, and run-off (Table 1). The standard AussieGRASS products were used to derive actively growing, senescent and dead vegetation biomass (Table 2).



AussieGRASS Environmental Calculator Products

Stocking rate

Burning

Climate

Soils

Trees

AussieGRASS outputs are gridded to 5x5km spatial resolution and were resampled to 250x250m to correspond to the map of degradation developed by Jackson & Prince [173]. Drought (2004-2007) and non-drought (2008-2011) periods were used. A per-pixel average was generated monthly: one for drought and one for non-drought.

#### 4.2.3. Degradation condition

Degradation estimates, mapped using reductions in NPP below the potential (Jackson & Prince [173]), were coupled with AussieGRASS outputs for each modeled grid cell. The degradation estimates, modeled in the BDT using the Local Net Production Scaling (LNS) approach, were created as follows (Jackson and Prince [18]): areas with similar environmental conditions (i.e. annual weather, soil properties, and proportion of tree cover) were analyzed by objective statistical methods to create land capability classes (LCCs). The 85<sup>th</sup> percentile of the frequency distribution of NPP within each LCC was used as the reference NPP (i.e. the best estimate of potential NPP). The difference between the reference and the actual NPP is the metric of degradation. Since the reductions were scaled by the reference NPP, they are called LNS values. All LNS values

were negative, with the lowest value corresponding to the greatest reduction in NPP. LNS values at or around zero indicated little-to-no degradation of NPP. LNS was measured in production units (gC m<sup>-2</sup> yr<sup>-1</sup>) and as a percentage (%; pLNS) of the reference. While LNS is the actual reduction in NPP, percent Table 4.1 AussieGRASS Environmental Calculator biomass, productivity, fire risk and run-off outputs. Variable names in brackets are the terms used in AussieGRASS.

Simulated land surface properties	Component units
Pasture Growth	kg ha <sup>-1</sup> month <sup>-1</sup>
Total Biomass (Total	kg ha⁻¹
Standing Dry Matter;	
TSDM)	
Percent Dead Biomass	%
(Curing Index)	
Grassfire Risk	%
Run-off (Potential Flow to	mm
Stream; PFTS)	

LNS represents the degree of degradation and is useful for comparisons across LCCs. Two degradation classes were created: average non-degraded (>30%) and average degraded ( $\leq$ 30%) for the 2004-2011 LNS.

#### 4.3. Results

### **4.3.1. Comparison of simulated land surface properties with satellite-derived NPP** Based on remotely-sensed reference NPP values, monthly simulated peak of

season pasture growth had a stronger correlation and higher linear regression slope coefficient during drought than during non-drought years (Table 4.3). The stronger correlation during drought years is possibly caused by the typically strong relationship between productivity and available moisture during drought conditions. Total biomass did not have a significant relationship with reference NPP in either drought or nondrought years, although drought years had a stronger correlation. The negative correlations between reference NPP and the percent dead biomass did not vary substantially between drought and non-drought years.

## **4.3.2. Comparison of model and remote sensing measurements of pasture condition** The strongest agreement between simulated land surface properties and LNS was

found in the northern portions of Spyglass (Figure 4.4), where the most substantial

reductions in NPP (low values for LNS) corresponded to areas of low growth, total biomass and percent dead biomass. Pasture growth appeared most similar to patterns of LNS. For each of LNS, pasture growth, total biomass, and percent dead biomass, nondrought years had the lowest values. Pasture growth and total biomass, specifically, were more than four times larger than in drought years.

Simulations of Riomass		Descriptio
		n
Total biomass = Green Biomass + Standing Dead Biomass	Eq . 1	Summation of all biomass, both green and dead, at the end of each time step ('total standing dry matter'). Downloade d product.
Percent Dead Biomass = Standing Dead Biomass/Total Biom	ua <b>lisq</b> . 2	Proportion of all biomass that is dead ('curing index'). Downloade d product.
Green Biomass = Total Biomass – Standing Dead biomass	Eq . 3	Total live (green) portion of all biomass, including new & old live production. Derived from downloade d products.
Standing Dead Biomass = Total biomass – Green biomass	Eq . 4	Total dead biomass. Derived from downloade d products.

Table 4.2 Monthly simulated land surface properties with equations and descriptions. All simulations of biomass have identical units (kg/ha), spatial resolution (5x5km) prior to resampling to 250 x 250m, and were calculated as monthly averages of drought (2004-2007) and non-drought years (2008-2011).

# 4.3.3. Comparison of intra-annual time-series for non-degraded and degraded conditions in drought and non-drought years

#### 4.3.3.1. Simulated land surface properties

Drought and non-drought years differed substantially between simulated land surface properties. For example, the averaged pasture growth for non-drought years was more than three times greater than in drought years (note the differences in vertical scale between drought and non-drought years in Figure 4.5). In non-drought years, phenological stages were more clearly defined and pasture growth decreased from April to June. As expected, the quantity of dead biomass peaked during periods of low pasture growth (i.e. February to May), while the difference between dead biomass and total biomass was greatest during periods of high pasture growth. In drought years, the growing season spanned more months than during non-drought years, but with an overall decreased amplitude and additional peaks throughout the season. These additional peaks, observed for green and total biomass, suggest either large variation in the timing of the monthly peaks between years or a consistent removal of biomass, natural (e.g. senescence) or human related (e.g. grazing), in most drought years. In both drought and non-drought years, degraded conditions resulted in reduced biomass accumulation (e.g. pasture growth and total biomass). While degraded areas had similar responses each month, for example the timing of peak pasture growth and total biomass, the values were reduced and in some cases appeared to be a near constant percentage of the non-degraded pixels. In drought years, the late greening (i.e. August) occurred for non-degraded pixels whereas degraded pixels did not have increased pasture growth.

Table 4.3 Regression of simulated-January productivity (Pasture Growth) and biomass (Total Biomass and Percent Dead Biomass), with reference NPP for the average of four drought (2004-2007) and four non-drought (2008-2011) years on reference NPP. Significance of correlation coefficient (r): for n > 2000; r > 0.19 is significant at the  $p \le 0.05$  (\*); r > 0.25 at  $p \le 0.01$  (\*\*); r > 0.32 at  $p \le 0.001$  (\*\*\*).

		Drought		Non- Drought		
Reference NPP	Pasture	Total	Percent	Pasture	Total	Percent
	Growth	Biomass	Dead	Growth	Biomass	Dead
	(kg ha⁻¹	(kg ha⁻¹)	Biomass	(kg ha⁻¹	(kg ha⁻¹)	Biomass
	mo⁻¹)		(%)	mo⁻¹)		(%)
Correlation	0.85 ***	0.48	0.55 ***	0.72***	0.08	0.56***
		***				
Slope	2.26 (Yes)	2.08	-0.05	1.92	-0.64	-0.08
coefficient		(No)	(Yes)	(Yes)	(No)	(Yes)
(significantly						
different from						
zero)						

In drought years, non-degraded areas had larger variations in pasture growth, total biomass, green biomass and dead biomass than degraded locations, where, on average, pasture variation decreased by 50% (Figure 4.5). The largest difference in pasture growth variation between non-degraded and degraded occurred in May, while March had the most substantial difference in between degradation conditions for total biomass. Late season accumulation of total biomass resulted in increased variation between both June to September and October to November.



# Drought Years (2004-2007)

# Non-Drought Years (2008-2011)



Figure 4.4 Maps of average LNS, peak of season pasture growth, total biomass, and percent dead biomass for drought (2004-2007) and non-drought (2008-2011) years. Note the difference in scale between drought and non-drought years.

Variation increased in non-drought years for each simulated land surface property

(Figure 4.5). Compared with drought years, non-drought years experienced similar

relationships between non-degraded and degraded variations but with differences

proportionally decreased each month and on average. However, the absolute differences

in variation between degradation conditions remained similar.



Figure 4.5 Comparison of monthly simulated land surface properties: Pasture Growth (kg ha-1 mo-1), Total Biomass (kg ha-1), Dead Biomass (kg ha-1), and Green Biomass (kg ha-1), showing the average of four drought years (2004-2007) and four non-drought years (2008-2011), for non-degraded (a, c) and degraded conditions (b, d) in the Spyglass Research Facility. Error bars show 1 standard deviation. The "degraded" and "non-degraded" condition was determined by the LNS value. Note the differences in vertical scale between drought and non-drought years.



Figure 4.6 Comparison of simulated land surface properties: Percent Dead Biomass (A), Grassfire Risk (B), and Run-off (C) partitioned by non-degraded and degraded conditions for drought (2004-2007) and non-drought (2008-2011) years. Error bars are one standard deviation.

Percent dead biomass was higher in drought years than in nondrought years, although grassfire risk was higher in non-drought years (Figure 4.6). This likely resulted from an increase in available fuel load in non-drought years. Grassfire risk remained constant throughout drought years. In non-drought years, however, grassfire risk increased most substantially between April and July, during the period of reduced growth and increased senescence (data not shown). Also, in non-drought years the difference between degraded and nondegraded percent dead biomass was more pronounced, where degraded pixels had higher values. Surprisingly, run-off was higher for non-degraded than degraded conditions, a possible

indication of reduced evaporation rates in non-degraded areas. Similarly, non-drought years had lower run-off. The significantly reduced run-off may have resulted from
additional surface friction by way of course pasture, which slowed run-off and encouraged infiltration of water.

# 4.3.4. Inter-annual variation

In drought and non-drought years, virtually all simulated land surface properties displayed significant differences in both non-degraded and degraded areas (Figure 4.7). In all cases the non-degraded values exceeded the degraded and were significantly different from their one-to-one line (i.e. relationship between non-degraded and degraded areas for each simulation; Figure 4.7). An exception was grassfire risk, which was not significantly different between degraded and non-degraded in drought or non-drought years; although in non-drought years the significance level was just outside of the significance (alpha= 0.07; Table 4.4). Furthermore, drought and non-drought regression lines were not significantly different from each other (alpha=0.38; Table 4.4). This indicated that differences in degradation condition were not directly related to increased fire susceptibility. The percent dead biomass for drought and non-drought years were also not significantly different from each other (alpha=0.97; Table 4.4) despite their non-degraded and degraded conditions being significantly difference from each other during both periods.

While there were differences in the effects of degradation of simulated land surface properties (Table 4.4), drought and non-drought years also had varying degrees of difference (Figure 4.7). Obviously non-drought years had a wider range of values and thereby emphasized the difference between non-degraded and degraded conditions. The distribution of values along simulated biomass gradients in non-drought years was characterized by their wide range of values, dispersion at high values, and variation around the best fit line. For example, non-drought pasture growth was mostly clustered

below 400 kg ha<sup>-1</sup> for both degradation conditions while only four, dispersed values were higher (Figure 4.7b) and a standard deviation of residuals that was nearly twice the drought value (Figure 4.7). Furthermore, for all measures of simulated biomass, slope coefficients were greater than 0.80 kg ha<sup>-1</sup> (i.e. nearer to the one-to-one line) in nondrought years (Figure 4.7B, 4.7d, 4.7f, 4.7h, & 4.7j). Conversely, slope coefficients for drought years were less than 0.65 kg ha<sup>-1</sup> for the same simulations of biomass (Figure 4.7a, 4.7c, 4.7e, 4.7g, & 4.7i). Similarly, and surprisingly, the coefficient of determination (R<sup>2</sup>) was higher in non-drought years compared with drought years. This indicated a stronger relationship between degradation conditions in non-drought years (Figure 4.7), despite an overall increased standard deviation of residuals (Figure 4.7). Noticeably different from simulations of biomass were the other simulated land surface properties, particularly run-off. Run-off had a greater standard deviation of residuals in drought years (3.6) than non-drought years (2.2; Table 4.4).

In non-drought years, the high slope coefficient (Figure 4.7) and correlation (Table 4.6) values suggested that some degraded sites were a percentage of the nondegraded locations (e.g. standing dead; Figure 4.7j). Interestingly, non-drought dead biomass was also not significantly different from the one-to-one line (alpha = 0.64; Table 4.6) but instead was offset from the one-to-one line (Figure 4.7). A possible explanation is that while intra-annual phenological transitions (i.e. green up, maturity, senescence, dormancy) resulted in similar mechanisms for biomass growth and decay, the simulated biomass was always consistently lower than the non-degraded locations throughout the entirety year. In drought years, however, the lower slope coefficient of best fit lines suggested increased differences between non-degraded and degraded locations. This case

was observed for total biomass in drought years (Figure 4.7e); as non-degraded total biomass increased, degraded total biomass only marginally increased (slope coefficient 0.46; Figure 4.7e) and appeared to differ substantially for the highest values. The resulting correlation between non-degraded and degraded total biomass was lower for drought years (r=0.86; Figure 4.7) than non-drought years (r=0.99; Figure 4.7).

The non-degraded and degraded slope coefficient values for percent dead biomass were nearly identical in both drought and non-drought years (1.1%; Figure 4.7k & 4.7l), although in areas with high percent dead biomass the degraded conditions were higher. Although the percent dead biomass across degradation conditions in each period were significantly different from the one-to-one line, the slopes did not differ significantly from each other whether drought or non-drought year (alpha=0.97; Table 4.4). This suggested that the impact of degradation was proportional regardless of rainfall quantity. Run-off, while significantly different between non-degraded and degraded locations in drought and non-drought years and also significantly different between drought and nondrought years, was the only simulated land surface property assessed that was more strongly correlated in drought years than non-drought years (Figure 4.7o & 4.7p).



Figure 4.7 Scatterplots comparing averages of monthly simulated land surface properties in non-degraded and degraded conditions in drought and non-drought years: growth (A & B), cumulative growth (C & D), total biomass (E & F), green biomass (G & H), dead biomass (I & J), percent dead (K & L), grassfire risk (M & N), and run-off (O & P). Note the differences in axes between each simulation of biomass accumulation. Continued on following page.



Figure 4.7. continued



Figure 4.7. continued

# 4.4. Discussion 4.4.1. Modeled simulations of biomass and its potential To develop meaningful comparisons between pasture biomass and its potential,

the gap must be bridged between interpretations of prognostic model outputs and satellite based observations [220-222]. The comparison between AussieGRASS Environmental Calculator simulations of biomass and estimated NPP potentials was especially appropriate given the similarities between the environmentally constraining data used in the simulation of biomass and the determination of LCCs (e.g. climate and soil; [215]). Soil properties, seasonal weather characteristics, and tree cover were used in the identification of reference sites for each year and the calculation of potential NPP [173], as well as modeled simulations of monthly biomass within the AussieGRASS model [110]. It should be noted that remotely-sensed observations of NPP are an amalgamation of not only biomass accumulation in response to favorable environmental conditions but also reductions in biomass due to environmental constraints. These constraints include natural (e.g. variable weather, soil conditions) and/or anthropogenic (e.g. management) factors [223]. A superficial difference between simulated biomass and potential NPP was the inclusion of management into the AussieGRASS model. The presence of management transformed AussieGRASS from a mechanistic prediction of pasture biomass potential to a representation of biomass variations resulting from human activity. The relationship between biomass variations and human activity was directly comparable to remotely-sensed observations of net primary productivity. Spatially explicit references of simulated biomass then became the best estimate of land potentials for modeled simulations of biomass and land surface properties alike (Table 3), a similar approach used by Jackson and Prince [173] to identify a reference for NPP. For potential NPP, persisting spatial variation in NPP within an LCC was a result of either additional environmental controls that were not included in LCC development (less likely) or related to the consequences of management (more likely). Jackson & Prince [173] thoroughly assessed the quality of NPP potentials through comparison with existing insitu maps of land potential and livestock carrying capacity [28,224], and found that NPP potentials responded more favorably to environmental constraints within and between LCCs than existing maps, and that variations in NPP could reliably be interpreted as responses to management. This ruled out the impact from omission of a key environmental factor in the development of LCCs and NPP potentials, while also

attributing differences in NPP to management. Accordingly, NPP potentials may be interpreted as managed areas with little-to-no impact on production, analogous to areas with simulated high pasture growth and green biomass. The strong correlation between NPP potentials and pasture growth in drought (r=0.85; Table 4.3) and non-drought years (r=0.72; Table 4.3) exemplifies this interpretation.

A portion of the residual unexplained variance between NPP and pasture growth (Table 4.3) may be attributed to other factors that contribute to NPP observations. Total biomass, as the sum of green and standing dead biomass, included green portions that were likely detected in remotely sensed observations of NPP. In drought years, the green component of total biomass was easily identified as the reference production within LCCs given the sharp contrast with areas of sparse vegetation cover. Total biomass, partially explains the drastic difference between drought and non-drought years in the

Table 4.4 List of non-degraded and degraded simulated land surface properties regression slopes that were not significant for drought years, non-drought years and between drought and non-drought years. Note: regressions were performed on averaged monthly values during drought and non-drought years; all other regression slopes not included were significantly different ( $\alpha = 0.05$ ) within degraded and non-degraded slopes or the difference between drought and non-drought years.

<b>Biomass Accumulation</b>	p-values
Regression (per month)	
Grassfire Risk (Drought	0.19
Years)	
Grassfire Risk (Non-Drought	0.07
Years)	
Non-Drought (Non-Drought	0.64
Years)	
Percent Dead (Drought &	0.97
Non-drought)	
Grassfire Risk (Drought &	0.38
Non-drought)	

correlation of NPP with pasture growth as well as NPP with total biomass at reference sites (Table 4.3). In drought years, when pasture growth was greatly reduced (Table 4.3), increased pasture growth corresponded to increased total biomass and thus resulted in an improved correlation between total biomass and NPP at reference sites. However, in nondrought years pasture growth and total biomass were increasingly independent of each other as evidenced by the difference in correlations with NPP and the substantially weakened relationship between NPP and total biomass (Table 4.3). This likely resulted from the variable sensitivity of biomass and NPP to discrepancies in moisture availability between drought and non-drought years. Such variations often characterize vegetation responses to rainfall in semi-arid regions [225-227]. As the difference between monthly green biomass and pasture growth increased, the sensitivity of NPP toward newer vegetation growth also increased. Vegetation indices, such as those used to calculate NPP [173], have increased sensitivity to new greening (i.e. recent pasture growth) as opposed to mature biomass only (i.e. a component of green biomass; [228]).

The contribution of non-green vegetation in estimates of potential NPP similarly cannot be ignored. While the correlation between NPP and the percent dead biomass were nearly identical for both drought and non-drought years (Table 4.3), simulations of increased biomass in non-drought years (Figure 4.5) resulted in higher quantities of dead biomass as well. In some semi-arid ecosystems additional uncertainty in estimates of green biomass have been attributed to abundant non-green biomass [229]. Moreover, non-green vegetation has been suggested to impact spatial distributions of reference sites within LCCs as well [205]. Likewise, non-green vegetation has an important influence on the carbon and water balance, not only affecting within season dynamics but also between season dynamics [2,230,231].

There were notable differences in the spatial and temporal resolving power between AussieGRASS simulations of biomass and land surface properties (monthly, 5x5km) and satellite observations of NPP (yearly, 250x250m; [173]) that contributed to residual disagreement between biomass potentials and potential NPP (Table 4.3). For

example, inter-annual (i.e. between seasons) production misses the intra-annual (i.e. within season) variation in production resulting from grazing pressure or instances of managed burning. While grazing is known to have within season variability, remotely sensed estimates of grazing pressure have proven difficult to reliably measure given the sporadic density, duration, and intensity of livestock grazing [232-235]. Because many important ecological phenomena occur at intra-annual scales (days, weeks, months, seasons), investigation at these temporal scales is essential for preventing misinterpretations that contradict established ecological principles (e.g. [35-37]). The increased gradient of response in drought years of NPP, pasture growth, and total biomass to reference NPP compared with non-drought years (Figure 4.1) corresponded well with established relationships between vegetation and varying moisture availability in water-stressed ecosystems [32,236-238].

# **4.4.2. Relating degradation to simulations of biomass and land surface properties 4.4.2.1. Human appropriation of NPP and degradation severity** Biomass accumulation is an essential component of ecosystem function

[239,240], especially in mixed tree-grass systems [241-244]. Studies of land cover change have long sought to disentangle anthropogenic and environmental influences on the terrestrial surface in Australian rangelands [28,65,107,245], specifically biomass. There were notable variations in biomass accumulation throughout the year in the Spyglass Research Facility, including differences between degradation conditions for AussieGRASS simulations. The indicator of degradation used in this and previous studies [173,205] identified anomalous low NPP where there was evidence of human activity. Observations of NPP, remotely sensed or otherwise, are always an amalgamation of management that generally reduce NPP from its unmanaged potential [246-250]. One

such measure of human intervention in altering biomass (i.e. harvesting, burning, or conversion) is human appropriation of net primary production (HANPP;[223]). Minimal management usually results in low HANPP from its production capacity [54,247,251-253], and thus higher observed production within an LCC. Conversely, increased management results in higher HANPP and more severe reductions to NPP that may be interpreted as human-induced [54,251]. A one-to-one relationship between modeled simulations in biomass under varying degradation conditions (i.e. non-degraded or degraded) resulted from a similar impact of human appropriation on biomass (Figure 4.7). As such, reductions in biomass in areas undergoing degradation indicated the severity of long-term degradation resulting from human appropriation (Figure 4.7). Global rates of HANPP have been shown to be sensitive to inter-annual variation in management patterns [54]. Between drought and non-drought years, an analogous result was found in this study: differences in simulated biomass (Table 6, Figures 4.5 & 4.7) and its intra-annual variation (Table 4.4 & 4.5) were related to (anthropogenic) degradation condition.

#### 4.4.2.2. Impact of degradation condition on production

In this study, the impact of degradation on simulated biomass was investigated inter-annually (Figure 4.7; Table 4.7) and intra-annually (Figures 4.5 & 4.7). Both interannual and intra-annual investigations revealed the deleterious effect degradation had on all components of the biomass. There were substantial reductions to simulated biomass at degraded sites for each component (Figures 4.5 & 4.7), regardless of whether it was a drought or non-drought period. The agreement between degradation condition and modeled simulations of biomass were encouraging and indicated that at least some of the differences were likely related to variations in management incorporated into the model. As expected, absolute differences in biomass between degradation conditions were largest in non-drought years (Figure 4.5), when increased rainfall better discriminated reductions in production due to non-environmental factors.

There was no observable delay in the timing of degraded peak pasture growth in either drought or non-drought years (Figure 4.5). This suggested that modeled simulations of biomass were particularly sensitive to rainfall events irrespective of longterm degradation. This result contradicted earlier findings that suggested a delayed onset of green-up as a characteristic of degradation in drylands [254]. In non-drought years, however, there was evidence that the month with the greatest variation in pasture growth differed between non-degraded and degraded conditions (Table 4.5). Interestingly in nondrought years, total biomass, a summation of all pasture biomass and its removal, displayed no substantial differences between degradation conditions in the peak timing of season total biomass (Figure 4.5). However, there were differences in drought years: nondegraded total biomass peaked in June, while degraded total biomass peaked in March (Figure 4.5). Although this delay in peak-total biomass may result from either green or dead biomass, the reduction in green biomass appeared to be the most substantial contribution to reduced total biomass (Figure 4.5). It is also possible that much of the decline in standing dead biomass at degraded locations was related to simulated losses from animal intake within the AussieGRASS model. For example, the nearly identical simulations of percent dead pasture for non-degraded and degraded conditions in both drought and non-drought years (Figure 4.7i & 4.7j), suggested that similar mechanisms of biomass growth and removal occurred over both degradation conditions and drought periods. The primary difference was the input pasture growth each month. Monthly

pasture growth was recorded as the accumulation of daily pasture growth on the final day of the month. Given similar environmental conditions, differences in pasture growth were a result of management (e.g. grazing pressure) that occurred at sub-monthly time steps.

#### 4.4.2.3. Response characteristics of biomass undergoing degradation

The examination of AussieGRASS simulations of biomass for drought and nondrought years revealed the divergent responses of biomass growth and decay to degradation within a single season. Two seemingly conflicting characteristics of vegetation production undergoing degradation have been suggested in Australian rangelands [21,28,59,65,224,255]: environmentally unresponsive production or subdued, environmentally responsive production. These phenomena, while appropriately investigated between years (e.g. [63,173,256]), have important implications for within season production (e.g. Figures 4.5 & 4.6).

The more commonly observed and straightforwardly identifiable, characteristic of degradation is the reduction of production that results in little-to-no vegetative response to favorable environmental conditions [47,257,258]. In these instances, the difference in production between phenological stages of maturity and dormancy are lessened as production fails to respond, in space and time, to favorable conditions (e.g. Figure 4.7 drought pasture growth). In this case, important mechanisms critical to the accumulation of primary production are disrupted. For example, intense grazing pressure or severe burning may cause soil compaction, which restricts water infiltration, nutrient uptake, and below surface production (e.g. roots), and also displaces moisture through run-off [7,40,141]. Each mechanism accelerates degradation processes, and both reduces production over a single season and restricts production in subsequent years due to the removal of protective foliage and limited seed dispersion [7].

The second characteristic of degradation observed in this study occurred when production in degraded areas responded temporally similarly to production in nondegraded areas, albeit consistently reduced through time (e.g. Figure 4.7f : non-drought total biomass). In this case, degradation was a percent reduction of the non-degraded areas throughout the year and not significantly different from the one-to-one line (e.g. non-drought dead biomass; Figure 4.7). Alternate stable states are characterized by these subtle reductions in production, instead of the clear degradation 'scars' that are more easily identified. The identification of alternate stable states of vegetation production is difficult owing to several factors; seemingly responsive production to environmental factors (e.g. increased production after rainfall events), difficulties in identification of appropriate reference sites that distinguish non-degraded production from surrounding areas, and the ease of identifying areas with the most severe reductions in productivity (degradation scars) while ignoring subtle reductions in production [173]. This alternative stable state implies that degradation, while constricting productivity, does not substantially alter biogeochemical mechanisms of intra-annual production accumulation [225]. For example, heavy grazing pressure that results in the removal of substantial quantities of green vegetation without disrupting soil processes, properties of nutrient uptake, and moisture availability [259]This phenomenon was most evident in nondrought years where non-degraded and degraded slope coefficient values were near or equal to 1.0 (Figure 4.7). Moreover, dead biomass was not significantly different from the one-to-one line between non-degraded and degraded areas in non-drought years (Figure 4.7). It should also be noted that although these characteristics of degradation on modeled simulations of biomass were largely expressed separately in drought and non-

drought years, there was also evidence of a continuity of trends between drought and non-drought years (e.g. percent dead & grassfire risk; Figure 4.7). These conflicting characteristics of degradation provided new insight into its potential effects on production.

# 4.4.3. Potential improvements to AussieGRASS

No current prognostic production models, to the authors' knowledge, incorporate degradation condition into assessments of future production. Instead, models including SSiB [199] and CASA [67] train simulations of production based upon satellite derived observations of vegetation (e.g. leaf area index). Given the agreement between degradation condition and variations in simulated production presented in this study (Figure 7), AussieGRASS simulations of biomass could be used to identify degradation susceptibility using existing inputs and outputs, including: total biomass, percent dead, stocking rate, burning, grassfire risk, percent cover, and run-off. In addition, the inclusion of ongoing degradation within the model would improve simulated responses of production to environmental controls: natural or otherwise. The inclusion of independent remotely-sensed assessments of degraded vegetation and its known mechanisms in Australian rangelands (e.g. [1,28,173,205]) would also enable simulated production to differentiate the intra-annual effect of degradation (e.g. nutrient cycling and water uptake), providing land managers with the opportunity to identify causes for reductions in production. Moreover, sensitivity analyses may inform which management strategies encourage land rehabilitation. While degradation is a long-term process that perseveres despite the return of favorable environmental conditions [7], persistent reductions in productivity that are simulated over multiple years could identify significant trends of land rehabilitation or warn of ongoing degradation processes.

The coupling of degradation condition with prognostic modelling holds significant opportunity to improve simulated production. AussieGRASS has the benefit of extensive, localized parameterization that is difficult to achieve at global scales. The results presented here suggest that comparable models available at global scales, such as Sim-CYCLE [260], can be used to simulate global carbon and water cycles and quantify the contribution of degradation on global change.

The economics of degradation are not well understood globally [253,261-263] or even locally in Australian rangelands [264,265]. Using AussieGRASS simulations of pasture production, secondary production (i.e. Animal live weight; Figure 4.3) may also be calculated under various severities of degradation. The reduction of secondary productivity in the Burdekin, where approximately 90% of land usage is reserved for beef production [113], has significant implications for Australian and global economic markets. The economic impact of reductions to animal live weight for even a single or a few paddocks, such as the Spyglass, likely has far reaching implications for land managers as well as the Queensland government. For example, the simulation of longterm degradation would serve as a valuable link for substantially reducing animal live weight.

#### **4.5.** Conclusions

The primary objective of this study was to assess the effects of long term degradation condition on biomass accumulation and the effect of environmental factors on the expression on degradation. In AussieGRASS, a prognostic model coupling local environmental factors and animal intake, provided context into potential mechanisms and consequences associated with instances of degradation. The comparison of satellitederived assessments of degradation condition using NPP with a pasture production model

enabled examination of the effects degradation on key components of pasture biomass production. The effects of degradation on biomass accumulation varied between components of pasture production. The results also shed new light on the relationships between degradation resulting in reduced NPP and variations in biomass accumulation expressed throughout the vegetative life cycle in Australian rangelands. The examination of within season (intra-annual) biomass accumulation revealed distinct growth curves associated with both degradation conditions (i.e. non-degraded and degraded). Finally, the interaction between degradation conditions and environmental conditions suggested varied expression of degradation. A possible feedback between environmental conditions and degradation conditions were found. Two distinct characteristics of degradation were expressed seemingly dependent on the presence, or absence of extended drought.

# Chapter 5 Synthesis, discussion and significance

5.1. Context

There is a pressing need to understand the dimensions of land degradation at both global and regional scales due to the deleterious effect it has on human-livelihood. Monitoring degradation is important in part due to its effect on food availability by reducing primary and secondary production, unwanted changes in species composition, unfavorable local-to-global land-atmosphere interactions (e.g. global carbon cycle, water and energy balances, etc.), and its long-term destructive effect on soil quality [7]. Furthermore, challenging land management decisions persist where land condition is poor and, as is often the case, the mechanisms that facilitated degradative processes are not well understood. Effective land use policy relies upon identifying, and mitigating, the causative factors that encourage the spread of degradation at regional scales.

There is a paucity of information regarding mechanisms of degradation around the world [111], especially in dryland systems. Conflicting estimates of the extent and severity of degradation in drylands are due to differing definitions as well as diverse, and often subjective, monitoring approaches. A key difficulty in any assessment of degradation is reconciling the numerous surrogates for degradation that exist, including productivity [48,130,266], soil erosion [40,141,153,267], soil quality and organic matter [14,101,268], vegetation patterns [62,212,269], dust generation [153,270,271], riparian health [272,273], and dry season cover [22,106,197,225,274]. Furthermore, previous studies have investigated the effects of degradation at several scales, which change the nature and interpretation of degradation. This dissertation uses net primary production (Chapter 2), fractional vegetation cover (Chapter 3), and biomass (Chapter 4) to identify and evaluate degradation at a regional scale.

The goals of the dissertation are to (1) identify the extent and severity of degradation using productivity as the primary surrogate, (2) compare the degradation of productivity to other known mechanisms of degradation, and (3) relate the expression of degradation to components of vegetation and varying environmental conditions.

## 5.2. Findings

There were three over overarching investigations in the dissertation, involving regional remote sensing techniques in the identification of anthropogenic degradation (Chapter 2), degradation and its impact on components of fractional vegetation cover (Chapter 3), and relationships between degradation and biomass (Chapter 4). From 2000 to 2013, there was substantial anthropogenic degradation present throughout the BDT region. Degradation, monitored in both space and time, was dispersed throughout the region (Figure 2.5), but also found within each sub-basin (Table 2.4 & Table 2.6). While dispersed across the BDT, degradation exhibited clear spatial patterns at regional scales (Figure 2.5). This demonstrated the utility of remote sensing in identifying, monitoring and ultimately characterizing degradation. Using regionally scaled remotely sensed data, degradation was distinguishable from non-degraded areas, including areas with little-tono reductions to their productivity. While only a small portion of the BDT was identified as 'deteriorating' from 2000 to 2013 (7%, Table 2.2), nearly 20% of the region was classified as currently 'degraded' using the 30% reduction threshold (Table 2.3). Furthermore, the severity of degradation found within degraded and/or deteriorating areas was substantial (-4.14 Mg C m<sup>-2</sup> y<sup>-1</sup>, Table 2.2). Annual reductions in NPP were also high (i.e. -2.14 MgC m<sup>-2</sup> y<sup>-1</sup> or -17% of the non-degraded reference; Table 2.2). River basins with the lowest annual rainfall experienced the most severe degradation (Table 2.4., Figure 2.5). The detection of degraded areas corroborated previous accounts of extensive

degradation in the BDT and corresponded to areas at risk for erosion (Figure 2.7). Degradation was strongly correlated with gradients of land use intensity (Table 2.8).

A critical component to anthropogenic degradation monitoring was to establish a reference from which current observations could be compared. The preceding chapters demonstrated an improved ability to model potential productivity (i.e. NPP) through the identification of spatial references in land capability classes (LCC). LCCs were created to replicate areas of near-homogeneous environmental conditions. The LCC approach (explained in 2.2.1) allowed for spatially distributed modeling of key environmental factors across the landscape without sparsely available decadal time-series, complex statistical modeling or highly parameterized mechanistic modeling. Within each LCC, locations that had little-to-no observable degradation were selected as the reference for potential NPP. LCC-selected reference sites out performed those selected using combined expert knowledge and fine resolution mapping in discriminating spatial rainfall patterns within and between classes (Figure 2.4 & Table 2.1) - the preeminent driver for naturebased change in dryland areas. This LCC approach was applied no only to NPP but also to the components of fractional cover to estimate land potentials in the absence of degradation in Chapter 3.

With NPP used as the surrogate for degradation condition, the components of fractional vegetation cover had high correlation with degradation. Photosynthetic vegetation (PV) was highly related to both NPP and degradation in space and time (Figure 3.3). The strong relationship between PV and NPP in space and time (Table 3.5) reinforced how strongly above-ground vegetation cover related to satellite derived NPP, which corresponded to both above and below ground components. The local scaling of

components of fractional cover, both in percentage of the total cover and its spatial configuration have potential for improving our understanding of degradation and its effects across a landscape (e.g. Figure 3.6). For example, increases in bare soil coverage from 2000 to 2013 revealed ongoing degradation that resulted in land entering into a permanent state of degradation.

Non-photosynthetic vegetation cover (NPV) had particularly interesting relationships with NPP (Figure 3.3); NPP and NPV had a poor relationship in space but had a strong relationship in time (Figure 3.5). Furthermore, the combination of local scaling of NPV and local scaling of NPP (called degradation in this dissertation) revealed clear spatial and temporal agreement – providing a promising way to characterize degradation. For example, low LNS values (i.e. severely degraded) with high local scaling of NPV (i.e. little-to-no reduction in NPV) were likely less susceptible to erosion than low LNS values with low local scaling of NPV (e.g. Figure 3.3). The regional patterns of NPV also suggested the type of human related activity (e.g. logging, grazing intensity, land conversion) that resulted in degradation (Table 3.9).

Independently simulated land surface properties, including biomass and pasture growth, were spatially correlated with degradation (Table 4.3 & Figure 4.4). Degradation had a clear restrictive effect on both simulated growth and overall biomass (Figure 4.5). The rate of pasture growth was slowed in degraded areas compared with non-degraded. This resulted from degradation related-unfavorable soil conditions for plant productivity and/or the presence of herbivores (e.g. livestock, native and feral). Degradation also reduced total biomass (i.e. the sum of green and dead biomass), with the largest

reductions occurring for green biomass. While dead biomass was also reduced under degraded conditions, its reduction did not approach that of green biomass.

Biomass and pasture growth, simulated using a prognostic model, proved sensitive to degradation during drought and non-drought years. Furthermore, identifying evidence of two states of degradation signaled an improved understanding of the phenomena. Differences in degradation between drought and non-drought years emphasized the relationship between environmental factors and observations of land condition (Figure 4.6 & Figure 4.7). Land surface properties in degraded areas, compared with non-degraded, showed no noticeable distinction in their progression throughout the season (Figure 4.7 & Figure 4.5).

#### 5.3. Recapitulation of research questions

Three major research questions were asked at the initiation of this dissertation (Figure 1.5), and were investigated throughout the duration of the studies in Chapters 2, 3, and 4. Presented below is a restatement of the research questions followed by responses that were informed by the findings in this dissertation.

**Research question 1: Is there evidence of human-induced degradation of NPP?** Yes, there was clear evidence of human-induced degradation of NPP throughout the BDT and with varying severities. We found that human-induced degradation was distinguishable from natural fluctuations in environment at a regional scale. We also found that degradation varied in space and time, but also contiguous areas with significant trends of land deterioration and substantial reductions in NPP that were identified as severely degraded. Furthermore, we found clear evidence of permanent degradation.

#### Research question 2: Are non-green components of vegetation sensitive to

**degradation?** Yes, non-green components of vegetation were sensitive to varying severities of degradation. However, the sensitivity was non-linear: non-photosynthetic components of vegetation were not strongly correlated with degradation in space, although the correlation was stronger through time. The accumulation of dead biomass was sensitive to degradation conditions in overall production and growth rates. The symptoms of degradation found in this dissertation, including reduced vegetative cover, coincided with increased erosion susceptibility and an overall reduction in plant material.

# **Research question 3:** Are the effects of degradation on NPP related to land use and do environmental factors interact? Yes, the effects of degradation on NPP were related to land use and environmental factors interacted with observations of degradation. We observed management patterns (e.g. fencing, clearing, etc.) that provided the strongest evidence of human influence on patterns of degradation. Also, the effect of drought and non-drought conditions emphasized and obscured observations of degradation. The most promising interaction between degradation and environmental factors was the evidence of degradation entering multiple stable states.

#### 5.4. Anthropogenic and environmental degradation

While substantial reductions in NPP were found across the BDT region as whole, there was considerable variation between river basins and between property boundaries. The link between anthropogenic disturbance and rates of degradation (detected here by low LNS) has been noted by Hill et al. [275] and Kairis et al. [276] and specifically in the BDT by McKeon et al. [29]. Independent evidence for anthropogenesis presented here includes correlation with the VAST map which, although not a map of vegetation

degradation, does distinguish varying degrees of human-related modification of native vegetation [277]. The good agreement of ranks of average LNS and the VAST classes (Table 2.8) is evidence that LNS was able to separate human-related degradation from natural variation, at least up to the end of the period of time used for the VAST map (2011). In addition, there was qualitative evidence from visual inspection of high resolution remotely-sensed imagery, such as abrupt differences across station boundaries (e.g. Figure 2.5b & Figure 2.5c) and coincidences of visible disturbance around livestock water points. The relationship between degradation, accelerated rates of erosion, and reduced vegetation cover is well-known [267] and erosion is the most widespread and recognizable characteristics of land degradation [139], also a primary impact on loss of soil carbon [14]. In the present study, there was a strong overall correlation of average LNS with hillslope erosion and gully density (Figure 2.7). In the BDT others have linked erosion with poor grazing management [197] and unsustainable agricultural production [9].

Assigning causal relationships to land degradation and natural or anthropogenic factors is difficult due to the close coupling between humans and their environment [60]. The LNS procedure offers one approach that attempts to isolate actual degradation of NPP from less favorable environmental conditions. However, without additional data on land usage, such as livestock numbers and management practices, the causes of the reductions by human-related activities are hard to determine [65]. The most commonly-cited management practices to reduce degradation are reduction in domestic livestock, reduction of feral herbivores, removal of watering points [65,278,279], fallowing [65,107], or by encouraging vegetation that is particularly resistant to overgrazing or able

to recover quickly after intense grazing [65,93,159]. Additional data are needed to interpret low LNS, particularly with field observation.

Given the extremely large areas of provincial, national, regional and global degradation that are frequently stated [51-54,280,281] and the far-reaching effects of degradation on human livelihoods [6,17], rigorous, quantitative and objective measurements are urgently needed. While reduction of NPP is a single type of degradation, it is a quantitative measure of the outcome of most forms of degradation relevant to human needs - but not all (e.g. loss of palatable species with no change in NPP; [167]). The widespread occurrence of degradation and its anthropogenic causes and effects require measurements having the large-area coverage and high spatial resolution provided by remote sensing, despite their limitations. LNS is founded on the concept of comparison of the actual conditions with their potential. As noted, there are several weaknesses in the technique that may affect the validity of the results, nevertheless, the fundamental concept of reduction from an explicit standard remains. There also remains a need for improvements in detection of appropriate reference standards, either by local scaling as in LNS or some other method.

The objectives of the many initiatives to arrest and remediate degradation have been summarized in the concept of Zero Net Land Degradation (ZNLD) [193]. ZNLD seeks to slow current rates of degradation such that the rates of land rehabilitation are, at the very least, equivalent to rates of deterioration [122], locally or elsewhere. Achievement of ZNLD depends on comprehensive monitoring to identify land states and trends of degradation. The study presented here used one approach to such regional assessment. While the feasibility of global land degradation neutrality has been debated [194], the

BDT is an example of a region that has seen a reversal of an overall trend toward degradation in productivity.

#### 5.5. Dimensions of degradation

To adequately investigate characteristics of degradation, the dynamics must be defined and evaluated. The dynamics of degradation subsist across numerous dimensions (e.g. space, time, and intensity) [60]. The fusion of two or more of these dimensions allows for robust monitoring of degradation [111]. Spatial characteristics of degradation relate to the extent and pattern of degradation on the land surface. The extent is valuable for summarizing current or past coverage of degradation and provides an indication to the prevalence of land that has entered, or is approaching, an unfavorable condition. The identification of degradation is essential for comparison with other spatial characteristics that exist on the land surface. These spatial relationships, whether subjective or using well defined autocorrelation techniques (e.g. Figure 2.7; Table 3.5; & Table 3.8), provide powerful insight into underlying causative factors. Patterns of degradation on a land surface (e.g. dispersed, random, and clustered) provide additional insight into the important triggering mechanisms of land condition change (e.g. Figure 2.5 & Figure 3.3). While natural and human factors may promote degradation, the patterns of vegetation undergoing degradation forecast potential effects [212]. Specifically, accelerated erosion maybe associated with vegetation configuration across the landscape [62,269].

Temporal dimensions of degradation are governed by the persistence of the reductions in productivity. The response of vegetation to degradation over extended periods reveals valuable characteristics regarding the effect of degradation (Figure 2.6 & Figure 3.5). Short-term reductions in productivity cannot indicate degradation because they may, in fact, be resultant from unfavorable environmental factors (e.g. drought, dry

spells) [7]. Persisting reductions, especially when favorable weather returns, provide a clear indication that key biological or soil processes are disrupted (Figure 2.6).

Intensity is perhaps the most critical dimension of degradation. The intensity of degradation refers to the severity of the unfavorable land condition. Intensity was described in the preceding chapters in two ways: absolute and relative. The absolute severity of degradation of production is the reduction in growth that is attributed to degradative processes [173]. Conversely, relative severity implies a differentiation in categorizing lands affected by degradation. In this dissertation, land areas were classified by their productive capacity (Chapter 2). Relative degradation is comparable across variable land types and dryland regions, and is arguably the best way to describe severity [286].

#### 5.6. Regional scale monitoring of degradation

Regional degradation is important for understanding management patterns that are relevant for policy makers as well as range managers and are transferable to other regions across the world [121,254]. Furthermore, many of the characteristics used to describe degradation (e.g. loss of vegetation cover, accelerated erosion) are difficult to monitor at fine scales [57]. At fine scales, differences in growth are associated with individual land management or related to animal preference [39,107,155]. At regional scales, degradation was attributable to management (e.g. clearing, grazing, and fencing; Figure 2.5). Remotely sensed data has become increasingly widespread, with varying temporal and spatial resolutions. Generally, however, the spatial coverage is proportional to the temporal repeat frequency (i.e. as spatial coverage increases, temporal repeats decrease and vice versa). The regional scale used in this dissertation, provided the best combination: 8-day repeat frequency, 250x250m pixel size, and visible-near infrared

spectral discrimination. The systematic dissemination of remotely sensed data allowed for automated image processing and continual analysis of land condition and degradation.

In the Burdekin, and across other Great Barrier Reef catchments, efforts to mitigate future degradation and rehabilitate land undergoing current degradation have resulted in millions of dollars' ear-marked for the investigation of regional management (http://www.nrm.gov.au/funding/2008/reef-rescue.html). Symptoms of degradation that are observed, such as erosion (Figure 2.5), on an individual field result in a negligible increase in sediment load and often go undetected in such assessments [65]. It is the combination of accelerated erosion (e.g. Figure 2.7), for example across a regional landscape that can substantially elevate sediment in waterways and result in irreversible harm to the Great Barrier Reef.

5.7. Relevance to climate studies, global carbon budget and food security Degradation in drylands has special significance due to the destructive effect it has on global phenomena [8,282] and its participation in the global carbon budget cannot be overstated [101]. Nevertheless, this phenomenon has been overlooked in most carbon studies. It must be acknowledged that other ecoregions (e.g. boreal, temperate and tropical forests) have higher densities of carbon [283]. However, the vast land area and carbon contained within drylands require assessments of carbon a priority when estimating the global carbon budget [101]. The intertwined interaction between human and natural processes in these regions only exacerbates disruptive fluctuations in carbon [111], often creating multiscale-positive feedbacks. The implications of these interactions may be felt locally (e.g. reduction in ground cover, invasive species) and globally (e.g. intercontinental dust transport). There is ongoing uncertainty that persists regarding the combination of current and potential sources of global carbon sequestration

[101,104,284,285]. However, effective monitoring of dryland carbon dynamics will result in improved global carbon accounting.

The effect of degradation on local and global climate is, in many respects, linked to changes in carbon fluctuations [254]. Global climate change is driven by reductions in terrestrial carbon sequestration that results in elevated atmospheric carbon [283], which has the prospect for accelerating global warming. Withal, even subtle modulations to local climate may result in unfavorable plant succession and environmental transformation. Combined with degradation these effects include: accelerated erosion and increased albedo and surface temperature [7]. Terrestrial carbon, within plants and soil, is often dramatically redistributed when erosion is severe and widespread [62,212]. The disruption of seed germination and desiccation of upper soil layers are negative feedbacks from increased surface temperature that restrict vegetation productivity and biomass[7]. In the absence of vegetation albedo increases and facilitates atmospheric warming. Undeniably several dimensions of degradation are closely intertwined with current and future carbon fluctuations.

#### 5.8. Future research

While this dissertation presented a thorough investigation of several components of degradation, it is necessary to continue investigating degradation. The primary emphasis was investigating land condition and the associated characteristics of degradation. However, there are two alternate components of degradation that require investigation: the long-term temporal monitoring of degradation and the objective linking of states and trends of degradation with land management. Particularly important for effectively assessing these components is an enhanced focus on the long-term monitoring of degradation. A longer duration of study, exceeding the 14-years investigated in this

dissertation, will make efforts to characterize the symptoms of degradation more efficient. With the additional years of data, from the end of the study period (i.e. 2013) until the present (i.e. 2017; +5 years), there is an opportunity to examine short term and long-term fluctuations in productivity over nearly two decades (e.g. 2000 to 2017). Prince [7] argued for the use of long term evaluation of degradation to further separate true degradation from the effects of climate. In many ways, long-term monitoring provides a clearer image of management patterns. For example, degradation that occurring during episodes of unfavorable environmental conditions (i.e. drought, heat waves), as in the Burdekin (Figure 1.4), revealed the intensity of management. In addition, time series fluctuations in degradation severity at a single location may be correlated to land management patterns through time. The next step in monitoring degradation must include aspects of degradation explored in this dissertation (i.e. extent, severity, trends), as well as predictive monitoring.

#### 5.8.1. Longer-term monitoring of land degradation

An analysis that calculates residuals or deviations from the long-term NPP-rainfall relationship, called Residual Trends (RESTREND; [63]), has been used in drylands to assess vegetation characteristics at sites possibly undergoing the process of land degradation [63,242,287,288]. The RESTREND method is based upon the near linear relationship between NPP and rainfall in semi-arid environments. To model NPP over a gradient of rainfall, RESTREND calculates a linear regression of NPP and rainfall observations. The residuals of NPP are then calculated as difference in the annual observations of NPP (oNPP) from the regression estimate of NPP (eNPP). Significant trends in NPP residuals that indicate ongoing land degradation are then analyzed during the study period. Annual NPP residuals are arranged sequentially through time (Figure 5.1). A linear regression slope is used to identify significant trends of residuals. Negative trends indicate observations of NPP differing further from the linear fit of NPP and rainfall through time, i.e. reduction in NPP possibly related to human factors. The slope indicates the rate at which a site is deviating from potential NPP given observed rainfall, i.e. change in land condition.



Bureau of Meteorology.



The benefit of the RESTREND technique is that it allows for examination of

vegetation condition at a single pixel through time. This is advantageous because

differences in NPP resulting from soil type or terrain effects are normalized.

# 5.8.2. Improving the RESTREND procedure

A time-series can be made of any trends obtained from the RESTREND method.

A segmented regression approach provides an opportunity to investigate the duration and magnitude of prevailing trends (Figure 5.1). Segmented linear regression can then determine statistically significant inflection points which correspond to changes in vegetation response to changing environments (Figure 5.1). The regression slope coefficient of each segmented regression indicate the magnitude of each negative trend. Significant and persistent negative trends may indicate the degradation of land condition.

Any variation in the strength of the rainfall -  $\Sigma$ NDVI correlation suggests environmental factors other than rainfall are limiting productivity and thus the need for additional environmental data (Figure 5.2). The distribution of rainfall through the growing season and pulses in temperature, solar exposure, and water vapor pressure deficit along with total seasonal rainfall may provide a more comprehensive description of variations in NPP related to environment.

To enhance the effectiveness of RESTREND, additional weather data (Figure 5.2), other than rainfall alone, could be tested and if significant, incorporated into the model. As with the development of LCCs, daily gridded synoptic weather data, including rainfall, minimum and maximum temperature, water vapor pressure deficit at 9am and 3pm, and solar exposure [133], from the Australian Bureau of Meteorology could be used.

Trends in NPP as estimated from the enhanced RESTREND procedure would then be compared against existing data sets including, if possible, Australian Grassland and Rangeland Assessment by Spatial Simulation (AussieGRASS) pasture model predictions of annual pasture yield. AussieGRASS is a highly-parameterized model for prediction of monthly production and other variables at 5km resolution over Queensland (covering the BDT region). Key data inputs include daily weather, soil and vegetation characteristics, tree density, and grazing pressure. Simulated outputs include runoff, infiltration, deep drainage, evapotranspiration, pasture growth and senescence, litter decay, and consumption of biomass by grazing animals. Outputs have undergone extensive field validation throughout the BDT region and were compared to degradation (Chapter 4). Linkages between NPP accumulation and response to these changing

environmental factors would be compared in literature with other dryland systems at varying scales.

#### 5.8.3. Examination of human factors contributing to reductions in NPP

The anthropogenic influence on plant production could be explored by relating persistently low NPP to indicators of land use intensity. Estimates of NPP loss from the LNS (used in this dissertation) or the RESTREND (described in section 5.8.1) procedures could be compared to identify locations which are currently degraded or undergoing land degradation. Evidence of degradation would be related to independent variables which indicate land use management and grazing pressure, including land use (type and intensity), stocking rate (density and type), land tenure type and lease holding duration, borehole (watering point) distribution, grazing enclosure properties (shape and size), fire return frequency, and surveys of land clearing. A spatially explicit, multiple regression approach would be used to identify which indicators of human management show the strongest relationship to patterns of reduced NPP. Identified relationships would provide insight to how each anthropogenic factor is related with observed reductions in NPP. Appropriate tests will be undertaken to avoid redundancy in explanatory variables.

Computational approaches, such as decision trees or regression trees could be used to explain significant relationships between degradation and management, and ultimately suggest linkages. Although causality is difficult to verify [289], correlations with associated uncertainty between land condition and management can be quantified. Furthermore, probabilistic approaches, including Bayesian Belief Network (BBN) modeling [290] could be used to further investigate likelihoods of human-environmental behavior. BBNs use priori evidence to train probability distributions, and predict potential outcomes between variables (e.g. environmental and management patterns).

BBN modeling improves degradation modeling by predicting current and future degradation based upon characteristics from known episodes (e.g. Dust Bowl in Central US, desertification Sahel) and thus eliminates the subjectivity that permeates many studies of degradation [207]. Symptoms of degradation (e.g. erosion) could be linked to management type and intensity to develop probabilistic relationships. A BBN approach would tether current observations with future possibilities. Lasting implications from this approach include the identification of current and future degradation, and the rehabilitation of degraded land along with the mitigation of degradation in areas where the requisite management practices exist.

Scale Terminology	Definition
Land Strata	Land unit of climate, landforms, soils and vegetation characteristics which for most practical purposes may be considered as uniform.
Land Capability Class (LCC)	Unit with homogeneous potential for specified human use.
Global Scale	A spatial scale that encompasses a geographic area relevant for continental or global study.
Regional Scale	A spatial scale that encompasses a geographic area ranging from several hundred hectares to millions of hectares (In the proposed study, the regional scale is 14 million hectares). This scale is relevant for country and large territory assessments.
Local Scale	A spatial scale that encompasses a geographic area representing less than 100 hectare (≤ 100 ha or 1km <sup>2</sup> ). This scale is relevant for field surveys and in-situ measurements.
Seasonal	Period of time relevant for major plant growth. In semi-arid areas, it usually coincides with rainfall cycles. In the Burdekin Dry Tropics region this ranges from August to July.
Annual	A yearly time step.
Inter-annual	Year to year time scale. In present study term relates to differences in vegetation growth between consecutive years.
Persistent	A time scale spanning greater than or equal to 10 years (≥ 10)
Land Condition	State the land referring to vegetation health (e.g. NPP, cover, biomass, species composition, etc.). Poor land condition is used to indicate possible degradation of vegetation.
Net Primary Productivity (NPP)	The amount of carbon uptake after subtracting plant respiration from gross primary productivity
Biomass	Total mass of organisms in a given area or volume

Glossary of Terms and Acronyms Explanation of terminology for spatial and temporal scales used in text.
Local NPP Scaling (LNS, Scaled)	Technique that can be unscaled for deriving an estimate of the spatial extent of land degradation
Grazing Land Management (GLM)	Land stratification to manage livestock on pasture so as to improve land condition and biodiversity
Moderate Resolution Imaging Spectroradiometer (MODIS)	Key remote sensing instrument aboard the Terra and Aqua satellites
Advanced Very High Resolution Radiometer (AVHRR)	Radiation-detection imager that can be used for remotely determining cloud cover and surface temperature
Normalized Difference Vegetation Index (NDVI)	Graphical measure used to assess live green vegetation; uses visible (red) and near-infrared bands
Enhanced Vegetation Index (EVI)	Optimized vegetation index with improved sensitivity to high biomass environments
Grass Production (GRASP) model	Model that simulates daily pasture growth and biomass using pasture utilization and ground cover
Australian Grassland and Rangeland Assessment (AussieGRASS)	A spatial implementation of GRASP that produces maps of simulated pasture growth and biomass
Vegetation Assets, States, and Transitions (VAST)	Classification that orders vegetation by degree of anthropogenic modification in a series of states
Residual Trends (RESTRENDS)	Method based on the residuals of the regression between NDVI and precipitation

Bibliography

- Karfs, R.; Holloway, C.; Pritchard, K.; Resing, J. Land condition photo standards for the burdekin dry tropics rangelands: A guide for practitioners; Burdekin Solutions Ltd and Queensland Department of Primary Industries and Fisheries: Townsville, 2009.
- 2. Guerschman, J.P.; Hill, M.J.; Renzullo, L.J.; Barrett, D.J.; Marks, A.S.; Botha, E.J. Estimating fractional cover of photosynthetic vegetation, non-photosynthetic vegetation and bare soil in the australian tropical savanna region upscaling the eo-1 hyperion and modis sensors. *Remote Sensing of Environment* **2009**, *113*.
- Safriel, U.; Adeel, Z. Dryland systems. In *Millennium Ecosystem* Assessment: Ecosystems and Human Well-being: Current State and Trends, Hassan, R.; Scholes, R.; Ash, N., Eds. Island Press: Washington, DC, 2005; Vol. 1, p 638.
- Reynolds, J.F.; Stafford Smith, D.M.; Lambin, E.F.; Turner, B.L.; Mortimore, M.; Batterbury, S.P.J.; Downing, T.E.; Dowlatabadi, H.; Fernandez, R.J.; Herrick, J.E., *et al.* Global desertification: Building a science for dryland development. *Science* 2007, *316*, 847-851.
- 5. Safriel, U. The assessment of global trends in land degradation. *Climate and Land Degradation* **2007**, 1-38.
- Adeel, Z. Findings of the global desertification assessment by the millennium ecosystem assessment a perspective for better managing scientific knowledge. In *Future of drylands*, Lee, C.; Schaaf, T., Eds. Springer, Po Box 17, 3300 Aa Dordrecht, Netherlands: 2008; pp 677-685.
- Prince, S.D. Spatial and temporal scales of measurement of desertification.
  Global desertification: Do humans create deserts? Reynolds, M.S.-S.a.J.F., Ed.
  Dahlem University Press: Berlin, 2002; pp 23-40.
- 8. Lal, R. Soil erosion and the global carbon budget. *Environment International* **2003**, *29*.
- 9. Montgomery, D.R. Soil erosion and agricultural sustainability. *PNAS* **2007**, *104*, 13268-13272.
- 10. Shakesby, R.A.; Wallbrink, P.J.; Doerr, S.H.; English, P.M.; Chafer, C.J.; Humphreys, G.S.; Blake, W.H.; Tomkins, K.M. Distinctiveness of wildfire effects on soil erosion in south-east australian eucalypt forests assessed in a global context. *Forest Ecology and Management* **2007**, *238*.
- 11. Hancock, G.R. A catchment scale assessment of increased rainfall and storm intensity on erosion and sediment transport for northern australia. *Geoderma* **2009**, *152*.
- 12. Li, L.; Du, S.; Wu, L.; Liu, G. An overview of soil loss tolerance. *Catena* **2009**, *78*.
- 13. Verheijen, F.G.A.; Jones, R.J.A.; Rickson, R.J.; Smith, C.J. Tolerable versus actual soil erosion rates in europe. *Earth-Science Reviews* **2009**, *94*.
- 14. Rajan, K.; Natarajan, A.; Kumar, K.S.A.; Badrinath, M.S.; Gowda, R.C. Soil organic carbon the most reliable indicator for monitoring land degradation by soil erosion. *Current Science* **2010**, *99*.

- 15. Bastin, G.N.; Pickup, G.; Chewings, V.H.; Pearce, G. Land degradation assessment in central australia using grazing gradient method. *The Rangeland Journal* **1993**, *15*, 190-216.
- 16. Ludwig, J.A.; Tongway, D.J.; Freudenberger, D.O.; Noble, J.C.; Hodgkinson, K.C. Landscape ecology, function and management: Principles from australia's rangelands. CSIRO Publishing: Melbourne, Australia, 1997.
- 17. UNCCD. United nations convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in africa. In *United Nations General Assembly*, New York, 1994.
- Reynolds, J.F.; Stafford Smith, D.M. Do humans cause deserts? In *Global desertification: Do humans create deserts*?, Reynolds, J.F.; Stafford Smith, D.M., Eds. <st1:place w:st="on"><st1:placename w:st="on">Dahlem <st1:placetype w:st="on">University Press: Berlin, 2002.
- 19. Geist, H.J.; Lambin, E.F. Dynamic causal patterns of desertification. *Bioscience* **2004**, *54*.
- 20. Letnic, M. Dispossession, degradation and extinction: Environmental history in arid australia. *Biodiversity and Conservation* **2000**, *9*, 295-308.
- 21. Ludwig, J.A.; Bastin, G.N.; Eager, R.W.; Karfs, R.; Ketner, P.; Pearce, G. Monitoring australian rangeland sites using landscape function indicators and ground- and remote-based techniques. *Environmental Monitoring and Assessment* **2000**, *64*, 167-178.
- 22. McKeon, G.; Hall, W.; Henry, B.; Stone, G.; Watson, I. *Pasture degradation and recovery in australia's rangelands: Learning from history*. Department of Natural Resources Mines and Energy Queensland: Brisbane, 2004.
- 23. Bartley, R.; Hawdon, A.; Post, D.A.; Roth, C.H. A sediment budget for a grazed semi-arid catchment in the burdekin basin, australia. *Geomorphology* **2007**, *87*.
- 24. Bastin, G.; ACRIS Management Committee, t. *Rangelands 2008* ACRIS Management Committee Canberra, 2008; p 233.
- 25. McKergow, L.A.; Prosser, I.P.; Hughes, A.O.; Brodie, J. Sources of sediment to the great barrier reef world heritage area. *Marine Pollution Bulletin* **2005**, *51*.
- 26. Palmer, M.A. Reforming watershed restoration: Science in need of application and applications in need of science. *Estuaries and Coasts* **2009**, *32*.
- Bastin, G.N.; Ludwig, J.A. Problems and prospects for mapping vegetation condition in australia's arid rangelands. *Ecological Management & Restoration* 2006, 7, S71-S74.
- 28. Karfs, R.A.; Abbott, B.N.; Scarth, P.F.; Wallace, J.F. Land condition monitoring information for reef catchments: A new era. *Rangeland Journal* **2009**, *31*.
- 29. McKeon, G.M.; Stone, G.S.; Syktus, J.I.; Carter, J.O.; Flood, N.R.; Ahrens, D.G.; Bruget, D.N.; Chilcott, C.R.; Cobon, D.H.; Cowley, R.A., *et al.* Climate change impacts on northern australian rangeland livestock carrying capacity: A review of issues. *Rangeland Journal* **2009**, *31*, 1-29.
- 30. Fensholt, R.; Langanke, T.; Rasmussen, K.; Reenberg, A.; Prince, S.D.; Tucker, C.; Scholes, R.J.; Le, Q.B.; Bondeau, A.; Eastman, R., *et al.* Greenness in semi-arid

areas across the globe 1981-2007 - an earth observing satellite based analysis of trends and drivers. *Remote Sensing of Environment* **2012**, *121*.

- 31. Charney, J.G. Dynamics of deserts and drought in the sahel. *Quarterly Journal of the Royal Meteorological Society* **1975**, *101*, 69.
- 32. Nicholson, S.E.; Tucker, C.J.; Ba, M.B. Desertification, drought, and surface vegetation: An example from the west african sahel. *Bulletin of the American Meteorological Society* **1998**, *79*.
- Prince, S.D.; De Colstoun, E.B.; Kravitz, L.L. Evidence from rain-use efficiencies does not indicate extensive sahelian desertification. *Global Change Biology* **1998**, 4, 359-374.
- 34. Anyamba, A.; Tucker, C.J. Analysis of sahelian vegetation dynamics using noaaavhrr ndvi data from 1981-2003. *Journal of Arid Environments* **2005**, *63*.
- 35. Hein, L.; de Ridder, N. Desertification in the sahel: A reinterpretation. *Global Change Biology* **2006**, *12*, 751-758.
- 36. Prince, S.D.; Wessels, K.J.; Tucker, C.J.; Nicholson, S.E. Desertification in the sahel: A reinterpretation of a reinterpretation. *Global Change Biology* **2007**, *13*, 1308-1313.
- Hein, L.; de Ridder, N.; Hiernaux, P.; Leemans, R.; de Wit, A.; Schaepman, M. Desertification in the sahel: Towards better accounting for ecosystem dynamics in the interpretation of remote sensing images. *Journal of Arid Environments* 2011, 75, 1164-1172.
- 38. Dregne, H.E.; Chou, N.T. Global desertification dimensions and costs. In *Degradation and restoration of arid lands*, Dregne, H.E., Ed. Texas Technical University: Lubbock, 1992.
- 39. Pickup, G.; Bastin, G.N.; Chewings, V.H. Identifying trends in land degradation in non-equilibrium rangelands. *Journal of Applied Ecology* **1998**, *35*.
- 40. Dregne, H.E. Land degradation in the drylands. *Arid Land Research and Management* **2002**, *16*.
- Behnke, R.H.; Scoones, I. Rethinking range ecology: Implications for rangeland management in africa. . In *Range ecology at disequilibrium*, R.H. Behnke, I.S., and C. Kerven, Ed. Overseas Development Institute: London, 1993; pp 1-30.
- 42. de Soyza, A.G.; Whitford, W.G.; Herrick, J.E.; Van Zee, J.W.; Havstad, K.M. Early warning indicators of desertification: Examples of tests in the chihuahuan desert. *Journal of Arid Environments* **1998**, *39*, 101-112.
- Zhang, K.F.; Li, X.W.; Zhou, W.H.; Zhang, D.X.; Yu, Z.R. Land resource degradation in china: Analysis of status, trends and strategye. *Int. J. Sustain. Dev. World Ecol.* 2006, 13, 397-408.
- 44. Lehouerou, H.N. Man and desertization in mediterranean region. *Ambio* **1977**, *6*, 363-365.
- 45. Safriel, U.N. Status of desertification in the mediterranean region. *Water Scarcity, Land Degradation and Desertification in the Mediterranean Region* **2009**.

- 46. Bajocco, S.; De Angelis, A.; Perini, L.; Ferrara, A.; Salvati, L. The impact of land use/land cover changes on land degradation dynamics: A mediterranean case study. *Environmental Management* **2012**, *49*, 980-989.
- 47. Prince, S.D. Mapping desertification in southern africa. In *Land change science: Observing, monitoring, and understanding trajectories of change on the earth's surface*, Gutman, G.; Janetos, A.; Justice, C.O., Eds. Kluwer: Dordrecht, Netherlands, 2004; pp 163-184.
- 48. Prince, S.D.; Becker-Reshef, I.; Rishmawi, K. Detection and mapping of long-term land degradation using local net production scaling: Application to zimbabwe. *Remote Sensing of Environment* **2009**, *113*, 1046-1057.
- 49. Pickup, G. Desertification and climate change the australian perspective. *Climate Research* **1998**, *11*.
- 50. Oldeman, L.R.; Hakkeling, R.T.A. World map of the status of human-induced soil degradation: An explanatory note (2nd revised edition). Centre, I.S.R.a.I., Ed. United Nations Environment Programme: 1991.
- 51. Oldeman, L.R. *The global extent of soil degradation*. 1994.
- 52. Kassas, M. Desertification a general-review. *Journal of Arid Environments* **1995**, *30*, 115-128.
- 53. Bridges, E.M.; Oldeman, L.R. Global assessment of human-induced soil degradation. *Arid Soil Research and Rehabilitation* **1999**, *13*.
- Zika, M.; Erb, K.H. The global loss of net primary production resulting from human-induced soil degradation in drylands. *Ecological Economics* 2009, *69*, 310-318.
- 55. Walker, B.H.; Janssen, M.A. Rangelands, pastoralists and governments: Interlinked systems of people and nature. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* **2002**, *357*, 719-725.
- 56. Scarth, P.; Byrne, M.; Danaher, T.; Henry, B.; Hassett, R.; Carter, J.; Timmers, P. In State of the paddock: Monitoring condition and trend in ground cover across queensland, Proceedings of the 13th Australasian Remote Sensing Conference, Canberra, Australia, 2006; Canberra, Australia.
- 57. Ludwig, J.A.; Bastin, G.N.; Wallace, J.F.; McVicar, T.R. Assessing landscape health by scaling with remote sensing: When is it not enough? *Landscape Ecology* **2007**, *22*, 163-169.
- 58. Jafari, R.; Lewis, M.M.; Ostendorf, B. An image-based diversity index for assessing land degradation in an and environment in south australia. *Journal of Arid Environments* **2008**, *72*, 1282-1293.
- 59. Bastin, G.; Schmidt, M.; P., O.R.; Karfs, R. In *Reporting change in landscape function using the queensland ground cover index*, Proceedings of the 16th Biennial Conference of the Australian Rangeland Society, Bourke, 2010; Waters, D.J.E.a.C., Ed. Australian Rangeland Society: Bourke.
- Reynolds, J.F.; Maestre, F.T.; Kemp, P.R.; Stafford-Smith, D.M.; Lambin, E. Natural and human dimensions of land degradation in drylands: Causes and consequences. In *Terrestrial ecosystems in a changing world*, Canadell, J.G.; Pataki, D.E.; Pitelka, L.F., Eds. Springer: Heidelberg, 2007; pp 247-257.

- 61. Pickup, G. Estimating the effects of land degradation and rainfall variation on productivity in rangelands: An approach using remote sensing and models of grazing and herbage dynamics. *Journal of Applied Ecology* **1996**, *33*.
- Ludwig, J.A.; Bastin, G.N.; Chewings, V.H.; Eager, R.W.; Liedloff, A.C. Leakiness: A new index for monitoring the health of arid and semiarid landscapes using remotely sensed vegetation cover and elevation data. *Ecological Indicators* 2007, 7.
- 63. Wessels, K.J.; Prince, S.D.; Malherbe, J.; Small, J.; Frost, P.E.; VanZyl, D. Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in south africa. *Journal of Arid Environments* **2007**, *68*.
- 64. Wessels, K.J.; Prince, S.D.; Reshef, I. Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. *Journal of Arid Environments* **2008**, *72*, 1940-1949.
- 65. Bastin, G.; Scarth, P.; Chewings, V.; Sparrow, A.; Denham, R.; Schmidt, M.; O'Reagain, P.; Shepherd, R.; Abbott, B. Separating grazing and rainfall effects at regional scale using remote sensing imagery: A dynamic reference-cover method. *Remote Sensing of Environment* **2012**, *121*, 443-457.
- 66. Running, S.W.; Coughlan, J.C. A general-model of forest ecosystem processes for regional applications .1. Hydrologic balance, canopy gas-exchange and primary production processes. *Ecological Modelling* **1988**, *42*, 125-154.
- 67. Potter, C.S.; Randerson, J.T.; Field, C.B.; Matson, P.A.; Vitousek, P.M.; Mooney, H.A.; Klooster, S.A. Terrestrial ecosystem production a process model-based on global satellite and surface data. *Global Biogeochemical Cycles* 1993, 7.
- 68. Paruelo, J.M.; Epstein, H.E.; Lauenroth, W.K.; Burke, I.C. Anpp estimates from ndvi for the central grassland region of the united states. *Ecology* **1997**, *78*.
- 69. Oesterheld, M.; DiBella, C.M.; Kerdiles, H. Relation between noaa-avhrr satellite data and stocking rate of rangelands. *Ecological Applications* **1998**, *8*.
- 70. Tucker, C.J.; Vanpraet, C.; Boerwinkel, E.; Gaston, A. Satellite remote-sensing of total dry-matter production in the senegalese sahel. *Remote Sensing of Environment* **1983**, *13*.
- 71. Tucker, C.J.; Vanpraet, C.L.; Sharman, M.J.; Vanittersum, G. Satellite remotesensing of total herbaceous biomass production in the senegalese sahel - 1980-1984. *Remote Sensing of Environment* **1985**, *17*.
- 72. Prince, S.D. A model of regional primary production for use with coarse resolution satellite data. *International Journal of Remote Sensing* **1991**, *12*.
- 73. Rasmussen, M.S. Assessment of millet yields and production in northern burkinafaso using integrated ndvi from the avhrr. *International Journal of Remote Sensing* **1992**, *13*.
- 74. Fensholt, R.; Sandholt, I.; Rasmussen, M.S.; Stisen, S.; Diouf, A. Evaluation of satellite based primary production modelling in the semi-arid sahel. *Remote Sensing of Environment* **2006**, *105*, 173-188.
- 75. Huete, A.R.; Tucker, C.J. Investigation of soil influences in avhrr red and nearinfrared vegetation index imagery. *International Journal of Remote Sensing* **1991**, *12*.

- 76. Prince, S.D.; Justice, C.O. Coarse resolution remote-sensing of the sahelian environment editorial. *International Journal of Remote Sensing* **1991**, *12*.
- 77. Tucker, C.J.; Newcomb, W.W.; Los, S.O.; Prince, S.D. Mean and inter-year variation of growing-season normalized difference vegetation index for the sahel 1981-1989. *International Journal of Remote Sensing* **1991**, *12*.
- 78. Prince, S.D.; De Colstoun, E.B.; Kravitz, L.L. Evidence from rain-use efficiencies does not indicate extensive sahelian desertification. *Global Change Biology* **1998**, *4*, 359-374.
- 79. Diouf, A.; Lambin, E.F. Monitoring land-cover changes in semi-arid regions: Remote sensing data and field observations in the ferlo, senegal. *Journal of Arid Environments* **2001**, *48*, 129-148.
- 80. Olsson, L.; Eklundh, L.; Ardo, J. A recent greening of the sahel trends, patterns and potential causes. *Journal of Arid Environments* **2005**, *63*.
- 81. Leys, J.; Smith, J.; MacRae, C.; Rickards, J.; Yang, X.; Randall, L.; Hairsine, P.; Dixon, J.; McTainsh, G. *Improving the capacity to monitor wind and water erosion: A review*; Department of Agriculture, Fisheries and Forestry, Commonwealth of Australia: 2009.
- 82. Graetz, R.D.; Pech, R.P.; Davis, A.W. The assessment and monitoring of sparsely vegetated rangelands using calibrated landsat data. *International Journal of Remote Sensing* **1988**, *9*.
- Wallace, J.F.; Holm, A.M.; Novelly, P.E.; Campbell, N.A. In Assessment and monitoring of rangeland vegetation composition using multi-temporal landsat data, The Proceedings of the 7th Australian Remote Sensing Conference, Melbourne, 1994; Melbourne, pp 1102-1109.
- 84. Bastin, G.N.; Pickup, G.; Pearce, G. Utility of avhrr data for land degradation assessment a case-study. *International Journal of Remote Sensing* **1995**, *16*.
- 85. Pickup, G. A simple-model for predicting herbage production from rainfall in rangelands and its calibration using remotely-sensed data. *Journal of Arid Environments* **1995**, *30*.
- 86. Hancock, G.R.; Coulthard, T.J.; Martinez, C.; Kalma, J.D. An evaluation of landscape evolution models to simulate decadal and centennial scale soil erosion in grassland catchments. *Journal of Hydrology* **2011**, *398*.
- 87. Nagler, P.L.; Daughtry, C.S.T.; Goward, S.N. Plant litter and soil reflectance. *Remote Sensing of Environment* **2000**, *71*.
- 88. Daughtry, C.S.T. Discriminating crop residues from soil by shortwave infrared reflectance. *Agronomy Journal* **2001**, *93*.
- 89. Daughtry, C.S.T.; Hunt, E.R.; Doraiswamy, P.C.; McMurtrey, J.E. Remote sensing the spatial distribution of crop residues. *Agronomy Journal* **2005**, *97*, 864-871.
- 90. Serbin, G.; Daughtry, C.S.T.; Hunt, E.R., Jr.; Brown, D.J.; McCarty, G.W. Effect of soil spectral properties on remote sensing of crop residue cover. *Soil Science Society of America Journal* **2009**, *73*, 1545-1558.
- 91. Serbin, G.; Daughtry, C.S.T.; Hunt, E.R., Jr.; Reeves, J.B., III; Brown, D.J. Effects of soil composition and mineralogy on remote sensing of crop residue cover. *Remote Sensing of Environment* **2009**, *113*, 224-238.

- 92. Kaptue, A.T.; Prihodko, L.; Hanan, N.P. On regreening and degradation in sahelian watersheds. *Proceedings of the National Academy of Sciences of the United States of America* **2015**, *112*, 12133-12138.
- 93. McKeon, G.; Hall, W.; Henry, B.; Stone, G.; Watson, I. *Pasture degradation and recovery in australia's rangelands: Learning from history*. Department of Natural Resources, Mines and Energy: 2004.
- 94. Nachtergaele, F.O. Land degradation assessment indicators and the lada project. In *Soil conservation and protection for europe (scape)*, 2002?
- 95. Stone, G.; Dorine Bruget; John Carter; Robert Hassett; Greg McKeon; David Rayner. *Land: Pasture production and condition*; Department of Natural Resources and Water, Queensland Government: 2007.
- 96. Abberton, M.; Conant, R.; Batello, C. *Grassland carbon sequestration: Management, policy and economics*. Plant Production and Protection Division Food and Agriculture Organization of the United Nations (FAO): Rome, 2010; Vol. Vol. 11.
- 97. Falloon, P.; Jones, C.D.; Cerri, C.E.; Al-Adamat, R.; Kamoni, P.; Bhattacharyya, T.; Easter, M.; Paustian, K.; Killian, K.; Coleman, K., *et al.* Climate change and its impact on soil and vegetation carbon storage in kenya, jordan, india and brazil. *Agriculture Ecosystems & Environment* **2007**, *122*, 114-124.
- 98. Harper, R.J.; Gilkes, R.J.; Hill, M.J.; Carter, D.J. Wind erosion and soil carbon dynamics in south-western australia. *Aeolian Research* **2010**, *1*, 129-141.
- Huxman, T.E.; Snyder, K.A.; Tissue, D.; Leffler, A.J.; Ogle, K.; Pockman, W.T.; Sandquist, D.R.; Potts, D.L.; Schwinning, S. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia* 2004, 141, 254-268.
- Izaurralde, R.C.; Williams, J.R.; Post, W.M.; Thomson, A.M.; McGill, W.B.; Owens, L.B.; Lal, R. Long-term modeling of soil c erosion and sequestration at the small watershed scale. *Climatic Change* 2007, *80*, 73-90.
- 101. Lal, R. Carbon sequestration in drylands. *Annals of Arid Zone* **2000**, *39*, 1-10.
- 102. Lal, R. Potential of desertification control to sequester carbon and mitigate the greenhouse effect. *Climatic Change* **2001**, *51*, 35-72.
- 103. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **2004**, *304*.
- Schuman, G.E.; Janzen, H.H.; Herrick, J.E. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 2002, *116*, 391-396.
- McKeon, G.M.; G. S. Stone; J. I. Syktus; J. O. Carter; N. R. Flood; D. G. Ahrens; D. N. Bruget; C. R. Chilcott; D. H. Cobon; R. A. Cowley, *et al.* Climate change impacts on northern australian rangeland livestock carrying capacity: A review of issues. *The Rangeland Journal* 2009, *31*, 1-29.
- 106. Stewart, J.B.; Rickards, J. *Developing national protocols to map ground cover management practices in cropping and grazing systems*; Australian Government Bureau of Rural Sciences, Canberra: 2010.

- 107. Bastin, G.; Pickup, G.; Chewings, V.; Pearce, G. Land degradation assessment in central australia using a grazing gradient method. *Rangeland Journal* **1993**, *15*, 190-216.
- 108. Bastin, G.; Committee, A.M. *Rangelands 2008 taking the pulse*; National Land and Water Resources Audit: Canberra., 2008.
- 109. Carter, J.O.; Brook, W.B.; McKeon, G.M.; Day, K.A.; Paull, C.J. Aussiegrass: Australian grassland and rangeland assessment by spatial simulation. In Applications of seasonal climate forecasting in agricultural and natural ecosystems-the australian experience, Hammer, G.; Nicholls, N.; Mitchell, C., Eds. Kluwer Academic Press: Netherlands, 2000; pp 329-350.
- 110. The Long Paddock, Q.G. Australian grassland and rangeland assessment by spatial simulation.
- 111. Reynolds, J.F.; Smith, D.M.; Lambin, E.F.; Turner, B.L., 2nd; Mortimore, M.; Batterbury, S.P.; Downing, T.E.; Dowlatabadi, H.; Fernandez, R.J.; Herrick, J.E., *et al.* Global desertification: Building a science for dryland development. *Science* 2007, *316*, 847-851.
- 112. Fensholt, R.; Rasmussen, K.; Nielsen, T.T.; Mbow, C. Evaluation of earth observation based long term vegetation trends intercomparing ndvi time series trend analysis consistency of sahel from avhrr gimms, terra modis and spot vgt data. *Remote Sensing of Environment* **2009**, *113*, 1886-1898.
- 113. Mellick; Hanlon, H. *The burdekin dry tropics natural resources management plan* (2005-2010); Burdekin Dry Tropics Board: 2005, 2005.
- 114. Lymburner, L.; Tan, P.; Mueller, N.; Thackway, R.; Lewis, A.; Thankappan, M.; Randall, L.; Islam, A.; Senarath, U. 250 metre dynamic land cover dataset (1st edition). 1 ed.; Australia, G., Ed. Canberra, 2010.
- 115. NQDT. *Nq dry tropics annual community report 2009/2010*; NQ Dry Tropics: Townsville, 2010.
- 116. NQDT. *Nq dry tropics annual community report 2010/2011*; NQ Dry Tropics Townsville, 2011.
- 117. Petheram, C.; McMahon, T.A.; Peel, M.C. Flow characteristics of rivers in northern australia: Implications for development. *Journal of Hydrology* **2008**, *357*, 93-111.
- 118. Rustomji, P.; Bennett, N.; Chiew, F. Flood variability east of australia's great dividing range. *Journal of Hydrology* **2009**, *374*, 196-208.
- 119. NQDT. *Nq dry tropics annual community report 2008/2009*; NQ Dry Tropics: Townsville, 2009.
- 120. Accatino, F.; De Michele, C.; Vezzoli, R.; Donzelli, D.; Scholes, R.J. Tree-grass coexistence in savanna: Interactions of rain and fire. *Journal of Theoretical Biology* **2010**, *267*, 235-242.
- 121. Prince, S.D. Where does desertification occur? Mapping dryland degradation at regional to global scales. In *The end of desertification? Disrupting environmental change in drylands*, Behnke, R.; Matimore, M., Eds. Springer: 2016.
- 122. Lal, R.; Safriel, U.; Boer, B. Zero net land degradation: A new sustainable development goal for rio+ 20; UNCCD: 2012.

- 123. UNCCD. Unccd secretariat policy brief on zero net land degradation a sustainable development goal for rio+20; United Nations Convention to Combat Desertification (UNCCD): Bonn, Germany, 2012.
- 124. Gifford, R.M. Carbon sequestration in australian grasslands: Policy and technical issues. In Integrated crop management grassland carbon sequestration: Management, policy and economics. Proceedings of the workshop on the role of grassland carbon sequestration in the mitigation of climate change, Abberton, M.; Conant, R.; Batello, C., Eds. Food and Agriculture Organization of the United Nations (FAO): Rome, April 2009, 2010; Vol. 11, pp 31-56.
- 125. Boer, M.; Smith, M.S. A plant functional approach to the prediction of changes in australian rangeland vegetation under grazing and fire. *Journal of Vegetation Science* **2003**, *14*, 333-344.
- 126. Stoms, D.M.; Hargrove, W.W. Potential ndvi as a baseline for monitoring ecosystem functioning. *International Journal of Remote Sensing* **2000**, *21*, 401-407.
- 127. Nusser, S.M.; Goebel, J.J. The national resources inventory: A long-term multiresource monitoring programme. *Environmental and Ecological Statistics* **1997**, *4*, 181-204.
- 128. Budde, M.E.; Tappan, G.; Rowland, J.; Lewis, J.; Tieszen, L.L. Assessing land cover performance in senegal, west africa using 1-km integrated ndvi and local variance analysis. *Journal of Arid Environments* **2004**, *59*, 481-498.
- O'Connor, T.G.; Haines, L.M.; Snyman, H.A. Influence of precipitation and species composition on phytomass of a semi-arid african grassland. *Journal of Ecology* 2001, *89*, 850-860.
- 130. Bai, Z.G.; Dent, D.L.; Olsson, L.; Schaepman, M.E. Proxy global assessment of land degradation. *Soil Use and Management* **2008**, *24*, 223-234.
- Boer, M.M.; Puigdefabregas, J. Assessment of dryland condition using spatial anomalies of vegetation index values. *International Journal of Remote Sensing* 2005, 26, 4045-4065.
- 132. Weymouth, G.; Mills, G.A.; Jones, D.; Ebert, E.E.; Manton, M.J. A continentalscale daily rainfall analysis system. *Australian Meteorological Magazine* **1999**, *48*.
- 133. Jones, D.A.; Wang, W.; Fawcett, R. High-quality spatial climate data-sets for australia. *Australian Meteorological and Oceanographic Journal* **2009**, *58*.
- 134. ACLEP. National soil data. 1 ed.; (ACLEP), A.C.L.E.P., Ed. National Committee on Soil and Terrain (NCST): Canberra, Australia, 2011.
- 135. Danaher, T.; Armston, J.; Collett, L.; ieee. A regression model approach for mapping woody foliage projective cover using landsat imagery in queensland, australia. *Igarss 2004: Ieee International Geoscience and Remote Sensing Symposium Proceedings, Vols 1-7: Science for Society: Exploring and Managing a Changing Planet* **2004**, 523-527.
- 136. DPI&F. *Stocktake: Balancing supply and demand.*; Department of Primary Industries and Fisheries: 2004.
- 137. Whish, G. Land types of queensland. 2.0 ed.; Team, G.L.M.W., Ed. Department of Employment, Economic Development and Innovation: Brisbane, 2011.

- 138. Lesslie, R.; Thackway, R.; Smith, J. *A national-level vegetation assets, states and transitions (vast) dataset for australia (version 2)*; Bureau of Rural Sciences: Canberra, 2010.
- 139. Ravi, S.; Breshears, D.D.; Huxman, T.E.; D'Odorico, P. Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology* **2010**, *116*.
- Bui, E.N.; Hancock, G.J.; Wilkinson, S.N. 'tolerable' hillslope soil erosion rates in australia: Linking science and policy. *Agriculture, Ecosystems & Environment* 2011, 144, 136-149.
- 141. Dregne, H.E. Erosion and soil productivity in australia and new-zealand. *Land Degradation and Rehabilitation* **1995**, *6*.
- 142. Gillieson, D.; Wallbrink, P.; Cochrane, A. Vegetation change, erosion risk and land management on the nullarbor plain, australia. *Environmental geology* **1996**, *28*, 145-153.
- 143. Webb, N.P.; McGowan, H.A. Approaches to modelling land erodibility by wind. *Progress in Physical Geography* **2009**, *33*, 587-613.
- 144. Webb, N.P.; Phinn, S.R.; McGowan, H.A. Visual assessment of the australian land erodibility model. *Journal of Arid Environments* **2009**, *73*, 678-682.
- 145. NLWRA. Catchment, river and estuary condition in australia : A summary of the national land and water resources audit's australian catchment, river and estuary assessment 2002. Audit, N.L.a.W.R., Ed. Natural Heritage Trust (Australia) & National Land & Water Resources Audit (Program : Australia): Turner, A.C.T., 2002.
- 146. Lu, H.; Gallant, J.; Processer, I.P.; Moran, C.; Priestley, G. Predication of sheet and rill erosion over the australian continent, incorporating monthly soil loss distribution. 13/01, C.L.a.W.T.R., Ed. Canberra, Australia, 2001.
- 147. Hughes, A.O.; Prosser, I.P.; Stevenson, J.; Scott, A.; Lu, H.; Gallant, J.; Moran, C.J. Gully erosion mapping for the national land and water resources audit. In *Technical Report 26/01*, Water, C.L.a., Ed. Canberra, Australia, 2001.
- 148. Running, S.W.; Nemani, R.R.; Heinsch, F.A.; Zhao, M.S.; Reeves, M.; Hashimoto, H. A continuous satellite-derived measure of global terrestrial primary production. *Bioscience* 2004, *54*, 547-560.
- 149. Cohen, J. A coefficient of agreement for nominal scales. *Educational and Psychological Measurement* **1960**, *20*, 37-46.
- 150. Visser, H.; de Nijs, T. The map comparison kit. *Environmental Modelling & Software* **2006**, *21*, 346-358.
- 151. DSITIA. Land cover change in queensland 2011–12: A statewide landcover and trees study (slats) report, 2014. 1 ed.; Department of Science, Information Technology, Innovation and the Arts, Brisbane.: Department of Science, Information Technology, Innovation and the Arts (DSITIA), 2014; p 3.
- 152. Ibrahim, Y.Z.; Balzter, H.; Kaduk, J.; Tucker, C.J. Land degradation assessment using residual trend analysis of gimms ndvi3g, soil moisture and rainfall in sub-saharan west africa from 1982 to 2012. *Remote Sensing* **2015**, *7*, 5471-5494.

- 153. Dregne, H.E. Desertification of arid lands. In *Physics of desertification*, El-Baz, F.; Hassan, M.H.A., Eds. Harwood Academic Publishers: Chur, Switzerland; New York, 1983; p 242.
- 154. Burke, I.C.; Lauenroth, W.K.; Coffin, D.P. Soil organic-matter recovery in semiarid grasslands implications for the conservation reserve program. *Ecological Applications* **1995**, *5*, 793-801.
- 155. Smith, J.G.; Eldridge, D.J.; Throop, H.L. Landform and vegetation patch type moderate the effects of grazing-induced disturbance on carbon and nitrogen pools in a semi-arid woodland. *Plant and Soil* **2012**, *360*, 405-419.
- 156. Su, Y.Z.; Li, Y.L.; Cui, H.Y.; Zhao, W.Z. Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, inner mongolia, northern china. *Catena* **2005**, *59*, 267-278.
- 157. Falge, E.; Tenhunen, J.; Baldocchi, D.; Aubinet, M.; Bakwin, P.; Berbigier, P.; Bernhofer, C.; Bonnefond, J.M.; Burba, G.; Clement, R., *et al.* Phase and amplitude of ecosystem carbon release and uptake potentials as derived from fluxnet measurements. *Agricultural and Forest Meteorology* **2002**, *113*, 75-95.
- 158. Falge, E.; Baldocchi, D.; Tenhunen, J.; Aubinet, M.; Bakwin, P.; Berbigier, P.; Bernhofer, C.; Burba, G.; Clement, R.; Davis, K.J., *et al.* Seasonality of ecosystem respiration and gross primary production as derived from fluxnet measurements. *Agricultural and Forest Meteorology* **2002**, *113*, 53-74.
- 159. Smith, D.M.S.; McKeon, G.M.; Watson, I.W.; Henry, B.K.; Stone, G.S.; Hall, W.B.; Howden, S.M. Learning from episodes of degradation and recovery in variable australian rangelands. *Proceedings of the National Academy of Sciences of the United States of America* **2007**, *104*, 20690-20695.
- 160. UNCCD. United nations convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in <st1:Place w:St="On">africa. In United Nations General Assembly, <st1:state w:st="on"><st1:place w:st="on">New York, 1994.
- 161. Myneni, R.B.; Nemani, R.R.; Running, S.W. Estimation of global leaf area index and absorbed par using radiative transfer models. *Ieee Transactions on Geoscience and Remote Sensing* **1997**, *35*, 1380-1393.
- 162. Coppin, P.; Jonckheere, I.; Nackaerts, K.; Muys, B.; Lambin, E. Digital change detection methods in ecosystem monitoring: A review. *International Journal of Remote Sensing* **2004**, *25*, 1565-1596.
- 163. Turner, D.P.; Ritts, W.D.; Cohen, W.B.; Gower, S.T.; Running, S.W.; Zhao, M.S.; Costa, M.H.; Kirschbaum, A.A.; Ham, J.M.; Saleska, S.R., et al. Evaluation of modis npp and gpp products across multiple biomes. *Remote Sensing of Environment* 2006, 102, 282-292.
- 164. Bai, Y.; Wu, J.; Xing, Q.; Pan, Q.; Huang, J.; Yang, D.; Han, X. Primary production and rain use efficiency across a precipitation gradient on the mongolia plateau. *Ecology* **2008**, *89*, 2140-2153.
- 165. Huete, A.; Didan, K.; Miura, T.; Rodriguez, E.P.; Gao, X.; Ferreira, L.G. Overview of the radiometric and biophysical performance of the modis vegetation indices. *Remote Sensing of Environment* **2002**, *83*, 195-213.

- 166. Nagler, P.L.; Inoue, Y.; Glenn, E.P.; Russ, A.L.; Daughtry, C.S.T. Cellulose absorption index (cai) to quantify mixed soil-plant litter scenes. *Remote Sensing* of Environment **2003**, *87*, 310-325.
- 167. Asner, G.P.; Heidebrecht, K.B. Desertification alters regional ecosystem-climate interactions. *Global Change Biology* **2005**, *11*, 182-194.
- 168. Ren, H.R.; Zhou, G.S.; Zhang, F.; Zhang, X.S. Evaluating cellulose absorption index (cai) for non-photosynthetic biomass estimation in the desert steppe of inner mongolia. *Chinese Science Bulletin* **2012**, *57*, 1716-1722.
- 169. Cao, X.; Chen, J.; Matsushita, B.; Imura, H. Developing a modis-based index to discriminate dead fuel from photosynthetic vegetation and soil background in the asian steppe area. *International Journal of Remote Sensing* **2010**, *31*, 1589-1604.
- 170. Asner, G.P.; Wessman, C.A.; Bateson, C.A.; Privette, J.L. Impact of tissue, canopy, and landscape factors on the hyperspectral reflectance variability of arid ecosystems. *Remote Sensing of Environment* **2000**, *74*, 69-84.
- 171. Huete, A.R.; Miura, T.; Gao, X. Land cover conversion and degradation analyses through coupled soil-plant biophysical parameters derived from hyperspectral eo-1 hyperion. *leee Transactions on Geoscience and Remote Sensing* **2003**, *41*, 1268-1276.
- 172. Guerschman, J.P.; Oyarzabal, M.; Malthus, T.; McVicar, T.; Byrne, G.; Randall, L. *Evaluation of the modis-based vegetation fractional cover product*; CSIRO: Canberra, Australia, 2012.
- 173. Jackson, H.; Prince, S.D. Degradation of net primary production in a semiarid rangeland. *Biogeosciences* **2016**, *13*, 4721-4734.
- 174. MacQueen, J.B. In Some methods for classification and analysis of multivariate observations, Proceedings of 5-th Berkeley Symposium on Mathematical Statistics and Probability, Berkeley, CA, 1967; University of California Press: Berkeley, CA, pp 281-297.
- 175. Chilcott, C.R.; McCallum, B.S.; Quirk, M.F.; Paton, C.J. *Grazing land management education package workshop notes - burdekin*; Meat and Livestock Australia Limited: Sydney, Australia, 2003.
- 176. Running, S.W. Modeling regional variation in net primary production of pinyonjuniper ecosystems. In *Remote sensing of biosphere functioning*, Hobbs, R.J.; Mooney, H.A., Eds. Springer-Verlag: New York, 1990; pp 65-86.
- 177. Huang, C.-y.; Asner, G.P.; Barger, N.N. Modeling regional variation in net primary production of pinyon-juniper ecosystems. *Ecological Modelling* **2012**, *227*, 82-92.
- 178. Bastin, G.N.; Pickup, G.; Pearce, G. Utility of avhrr data for land degradation assessment - a case-study. *International Journal of Remote Sensing* **1995**, *16*, 651-672.
- 179. Dregne, H. Land degradation in the drylands. *Arid land research and management* **2002**, *16*, 99 132.
- 180. McAlpine, C.A.; Etter, A.; Fearnside, P.M.; Seabrook, L.; Laurance, W.F. Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from queensland (australia), colombia and

brazil. *Global Environmental Change-Human and Policy Dimensions* **2009**, *19*, 21-33.

- 181. Barson, M.; Randall, L.; Bordas, V. *Land cover change in australia. Results of the collaborative bureau of rural sciences—state agencies' project on remote sensing of land cover change*; Bureau of Rural Sciences: Kingston ACT, Australia, 2000.
- Lepers, E.; Lambin, E.F.; Janetos, A.C.; DeFries, R.; Achard, F.; Ramankutty, N.; Scholes, R.J. A synthesis of information on rapid land-cover change for the period 1981-2000. *Bioscience* 2005, 55, 115-124.
- 183. Fensham, R.J. Land clearance and conservation of inland dry rainforest in north queensland, australia. *Biological Conservation* **1996**, *75*, 289-298.
- 184. Catterall, C.P.; Kingston, M. Human populations, bushland distribution in south east queensland and the implications for birds. In *Birds and their habitats: Status and conservation in queensland.*, Catterall, C.P.; Driscoll, P.V.; Hulsman, K.; Muir, D.; Taplin, A., Eds. Queensland Ornithological Society Inc.: 1993.
- 185. Sinclear, L.K.; Jermyn, D.; Preston, R.A. Status and change of remnant vegetation in south-east queensland 1974–1989; Queensland Department of Housing, Local Government and Planning, Queensland Department of Primary Industries, Forest Service: Brisbane, Australia, 1993.
- 186. Myers, N. Threatened biotas: "Hot spots" In tropical forests. *The Environmentalist* **1988**, *8*, 187-208.
- 187. Woinarski, J.C.Z. Biodiversity conservation in tropical forest landscapes of oceania. *Biological Conservation* **2010**, *143*, 2385-2394.
- 188. Rasiah, V.; Florentine, S.K.; Williams, B.L.; Westbrooke, M.E. The impact of deforestation and pasture abandonment on soil properties in the wet tropics of australia. *Geoderma* **2004**, *120*, 35-45.
- 189. Brown, J.R.; Scanlan, J.C.; McIvor, J.G. Competition by herbs as a limiting factor in shrub invasion in grassland: A test with different growth forms. *Journal of Vegetation Science* **1998**, *9*, 829-836.
- 190. Jones, R.J. Steer gains, pasture yield and pasture composition on native pasture and on native pasture oversewn with indian couch (bothriochloa pertusa) at three stocking rates. *Australian Journal of Experimental Agriculture* **1997**, *37*, 755-765.
- Silcock, R.G.; Hall, T.J.; Filet, P.G.; Kelly, A.M.; Osten, D.; Schefe, C.M.; Knights,
  P.T. Floristic composition and pasture condition of aristida/bothriochloa pastures in central queensland. I. Pasture floristics. *Rangeland Journal* 2015, 37, 199-215.
- 192. Kutt, A.S.; Fisher, A. Increased grazing and dominance of an exotic pasture (bothriochloa pertusa) affects vertebrate fauna species composition, abundance and habitat in savanna woodland. *Rangeland Journal* **2011**, *33*, 49-58.
- 193. Stavi, I.; Lal, R. Achieving zero net land degradation: Challenges and opportunities. *Journal of Arid Environments* **2015**, *112*, 44-51.
- 194. Grainger, A. Is land degradation neutrality feasible in dry areas? *Journal of Arid Environments* **2015**, *112*, 14-24.
- 195. Hilimire, K. Integrated crop/livestock agriculture in the united states: A review. *Journal of Sustainable Agriculture* **2011**, *35*, 376-393.

- 196. Buendia, C.; Vericat, D.; Batalla, R.J.; Gibbins, C.N. Temporal dynamics of sediment transport and transient in-channel storage in a highly erodible catchment. *Land Degradation & Development* **2016**, *27*, 1045-1063.
- Bartley, R.; Roth, C.H.; Ludwig, J.; McJannet, D.; Liedloff, A.; Corfield, J.; Hawdon, A.; Abbott, B. Runoff and erosion from australia's tropical semi-arid rangelands: Influence of ground cover for differing space and time scales. *Hydrological Processes* 2006, 20.
- 198. Shinoda, M.; Gillies, J.A.; Mikami, M.; Shao, Y. Temperate grasslands as a dust source: Knowledge, uncertainties, and challenges. *Aeolian Research* **2011**, *3*, 271-293.
- 199. Xue, Y.; Sellers, P.J.; Kinter, J.L.; Shukla, J. A simplified biosphere model for global climate studies. *Journal of Climate* **1991**, *4*, 345-364.
- 200. Xue, Y.K.; Bastable, H.G.; Dirmeyer, P.A.; Sellers, P.J. Sensitivity of simulated surface fluxes to changes in land surface parameterizations a study using abracos data. *Journal of Applied Meteorology* **1996**, *35*, 386-400.
- 201. Jackson, H.; Prince, S.D. Degradation of net primary production in a semi-arid rangeland. *Biogeosciences* **2016**, *13*, 4721-4734.
- 202. Wessels, K.J. Monitoring land degradation in southern africa by assessing changes in primary productivity. University of Maryland, College Park, MD, 2005.
- 203. Albalawi, E.K.; Kumar, L. Using remote sensing technology to detect, model and map desertification: A review. *Journal of Food Agriculture & Environment* **2013**, *11*, 791-797.
- Thomas, R.J.; Eddy de Pauw; Manzoor Qadir; Ahmed Amri; Mustapha Pala; Amor Yahyaoui; Mustapha El-Bouhssini; Michael Baum; Iñiguez, L.; Shideed, K.
  Increasing the resilience of dryland agro-ecosystems to climate change. SAT eJournal | An Open Access Journal published by ICRISAT 2007, 4, 1-37.
- 205. Jackson, H.; Prince, S.D. Degradation of non-photosynthetic vegetation in a semiarid rangeland. *Remote Sensing* **2016**, *8*.
- 206. Tamene, L.; Le, Q.B. Estimating soil erosion in sub-saharan africa based on landscape similarity mapping and using the revised universal soil loss equation (rusle). *Nutrient Cycling in Agroecosystems* **2015**, *102*, 17-31.
- 207. Katyal, J.C.; Vlek, P.L.G. *Desertification concept, causes and amelioration*; **CENTER FOR DEVELOPMENT RESEARCH (ZEF)**: University of Bonn, 2000.
- Spinoni, J.; Vogt, J.; Naumann, G.; Carrao, H.; Barbosa, P. Towards identifying areas at climatological risk of desertification using the koppen-geiger classification and fao aridity index. *International Journal of Climatology* 2015, 35, 2210-2222.
- 209. Vicente-Serrano, S.; Cabello, D.; Tomás-Burguera, M.; Martín-Hernández, N.; Beguería, S.; Azorin-Molina, C.; Kenawy, A. Drought variability and land degradation in semiarid regions: Assessment using remote sensing data and drought indices (1982–2011). *Remote Sensing* **2015**, *7*, 4391.
- Collatz, G.J.; Ribas-Carbo, M.; Berry, J.A. Coupled photosynthesis-stomatal conductance model for leaves of c4 plants. *Australian Journal of Plant Physiology* 1992, 19, 519-538.

- 211. Ludwig, J.A.; Tongway, D.J. Spatial-organization of landscapes and its function in semiarid woodlands, australia. *Landscape Ecology* **1995**, *10*.
- 212. Ludwig, J.A.; Eager, R.W.; Liedloff, A.C.; Bastin, G.N.; Chewings, V.H. A new landscape leakiness index based on remotely sensed ground-cover data. *Ecological Indicators* **2006**, *6*, 327-336.
- 213. Berry, P.A.M.; Carter, J. Altimeter-derived soil moisture determination global scope and validation. *Grace, Remote Sensing and Ground-Based Methods in Multi-Scale Hydrology* **2011**, *343*, 92-97.
- 214. Fraser, G.W.; Carter, J.O.; McKeon, G.M.; Day, K.A. A new empirical model of sub-daily rainfall intensity and its application in a rangeland biophysical model. *Rangeland Journal* **2011**, *33*, 37-48.
- 215. Herr, A.; O'Connell, D.; Farine, D.; Dunlop, M.; Crimp, S.; Poole, M. Watching grass grow in australia: Is there sufficient production potential for a biofuel industry? *Biofuels Bioproducts & Biorefining-Biofpr* **2012**, *6*, 257-268.
- 216. The State of Queensland, Q.D.o.E.a.H.P. *Reef water quality protection plan secretariat: first report card 2009 baseline* Brisbane, QLD, 2011.
- 217. Rickert, K.G.; Stuth, J.W.; McKeon, G.M. Modelling pasture and animal production. In *Field and laboratory methods for grassland and animal production research*, Mannetje, L.T.; Jones, R.M., Eds. CABI publishing: New York, 2000; pp 29-66.
- 218. Jeffrey, S.J.; Carter, J.O.; Moodie, K.B.; Beswick, A.R. Using spatial interpolation to construct a comprehensive archive of australian climate data. *Environmental Modelling & Software* **2001**, *16*, 309-330.
- 219. Hassett, R.C.; Wood, H.L.; Carter, J.O.; Danaher, T.J. A field method for statewide ground-truthing of a spatial pasture growth model. *Australian Journal of Experimental Agriculture* **2000**, *40*, 1069-1079.
- Potter, C.; Klooster, S.; Myneni, R.; Genovese, V.; Tan, P.N.; Kumar, V. Continental-scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982-1998. *Global and Planetary Change* 2003, *39*, 201-213.
- 221. Potter, C.; Klooster, S.; Huete, A.; Genovese, V. Terrestrial carbon sinks for the united states predicted from modis satellite data and ecosystem modeling. *Earth Interactions* **2007**, *11*.
- 222. Lucas, N.S.; Curran, P.J. Forest ecosystem simulation modelling: The role of remote sensing. *Progress in Physical Geography* **1999**, *23*, 391-423.
- 223. Vitousek, P.M.; Ehrlich, P.R.; Ehrlich, A.H.; Matson, P.A. Human appropriation of the products of photosynthesis. *Bioscience* **1986**, *36*, 368-373.
- Karfs, R.A.; Wallace, J.F.; Ieee. An analysis of temporal change at rangeland monitoring sites using remote sensing in northwest australia. *Igarss 2001: Scanning the Present and Resolving the Future, Vols 1-7, Proceedings* 2001, 988-990.
- 225. Gillson, L.; Hoffman, M.T. Rangeland ecology in a changing world. *Science* **2007**, *315*, 53-54.

- 226. Lehouerou, H.N. Climate change, drought and desertification. *Journal of Arid Environments* **1996**, *34*, 133-185.
- 227. Loeser, M.R.R.; Sisk, T.D.; Crews, T.E. Impact of grazing intensity during drought in an arizona grassland. *Conservation Biology* **2007**, *21*, 87-97.
- 228. Rishmawi, K.N.; Prince, S.D.; Xue, Y. Vegetation responses to climate variability in the northern arid to sub-humid zones of sub-saharan africa. *Submitted* **2016**.
- 229. Hufkens, K.; Bogaert, J.; Dong, Q.H.; Lu, L.; Huang, C.L.; Ma, M.G.; Che, T.; Li, X.; Veroustraete, F.; Ceulemans, R. Impacts and uncertainties of upscaling of remote-sensing data validation for a semi-arid woodland. *Journal of Arid Environments* **2008**, *72*, 1490-1505.
- 230. Funk, C.C.; Brown, M.E. Intra-seasonal ndvi change projections in semi-arid africa. *Remote Sensing of Environment* **2006**, *101*, 249-256.
- 231. Zhang, X.Y.; Friedl, M.A.; Schaaf, C.B.; Strahler, A.H.; Hodges, J.C.F.; Gao, F.; Reed, B.C.; Huete, A. Monitoring vegetation phenology using modis. *Remote Sensing of Environment* **2003**, *84*, 471-475.
- Bastin, G.N.; Ludwig, J.A. Problems and prospects for mapping vegetation condition in australia's arid rangelands. *Ecological Management & Restoration* 2006, 7, S71-S74.
- 233. Linstadter, A.; Schellberg, J.; Bruser, K.; Garcia, C.A.M.; Oomen, R.J.; du Preez, C.C.; Ruppert, J.C.; Ewert, F. Are there consistent grazing indicators in drylands? Testing plant functional types of various complexity in south africa's grassland and savanna biomes. *Plos One* **2014**, *9*, 15.
- 234. Lohmann, D.; Tietjen, B.; Blaum, N.; Joubert, D.F.; Jeltsch, F. Shifting thresholds and changing degradation patterns: Climate change effects on the simulated long-term response of a semi-arid savanna to grazing. *Journal of Applied Ecology* 2012, 49, 814-823.
- 235. Pickup, G.; Chewings, V.H. Estimating the distribution of grazing and patterns of cattle movement in a large arid zone paddock. *International Journal of Remote Sensing* **1988**, *9*, 1469-1490.
- 236. Nicholson, S.E. Climatic and environmental change in africa during the last two centuries. *Climate Research* **2001**, *17*, 123-144.
- 237. Huxman, T.E.; Smith, M.D.; Fay, P.A.; Knapp, A.K.; Shaw, M.R.; Loik, M.E.; Smith, S.D.; Tissue, D.T.; Zak, J.C.; Weltzin, J.F., *et al.* Convergence across biomes to a common rain-use efficiency. *Nature* **2004**, *429*, 651-654.
- 238. Huxman, T.E.; Snyder, K.A.; Tissue, D.; Leffler, A.J.; Ogle, K.; Pockman, W.T.; Sandquist, D.R.; Potts, D.L.; Schwinning, S. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia* **2004**, *141*, 254-268.
- Yachi, S.; Loreau, M. Does complementary resource use enhance ecosystem functioning? A model of light competition in plant communities. *Ecology Letters* 2007, 10, 54-62.
- 240. Buchmann, N. Plant ecophysiology and forest response to global change. *Tree Physiology* **2002**, *22*, 1177-1184.

- 241. Bai, Z.G.; Conijn, J.G.; Bindraban, P.S.; Rutgers, B. *Global changes of remotely* sensed greenness and simulated biomass production since 1981. Towards mapping global soil degradation; ISRIC: Wageningen, 2012.
- 242. Hirata, M.; Koga, N.; Shinjo, H.; Fujita, H.; Gintzburger, G.; Ishida, J.; Miyazaki, A. Measurement of above-ground plant biomass, forage availability and grazing impact by combining satellite image processing and field survey in a dry area of north-eastern syria. *Grass and Forage Science* **2005**, *60*.
- 243. Beringer, J.; Hutley, L.B.; Hacker, J.M.; Neininger, B.; U, K.T.P. Patterns and processes of carbon, water and energy cycles across northern australian landscapes: From point to region. *Agricultural and Forest Meteorology* **2011**, *151*, 1409-1416.
- 244. Otieno, D.O.; K'Otuto, G.O.; Jakli, B.; Schrottle, P.; Maina, J.N.; Jung, E.; Onyango, J.C. Spatial heterogeneity in ecosystem structure and productivity in a moist kenyan savanna. *Plant Ecology* **2011**, *212*, 769-783.
- 245. Northup, B.; Brown, J.; Ash, A. Grazing impacts on spatial distribution of soil and herbaceous characteristics in an australian tropical woodland. *Agroforestry Systems* **2005**, *65*, 137-150.
- 246. Erb, K.H.; Krausmann, F.; Lucht, W.; Haberl, H. Embodied hanpp: Mapping the spatial disconnect between global biomass production and consumption. *Ecological Economics* **2009**, *69*, 328-334.
- 247. Fetzel, T.; Niedertscheider, M.; Haberl, H.; Krausmann, F.; Erb, K.H. Patterns and changes of land use and land-use efficiency in africa 1980-2005: An analysis based on the human appropriation of net primary production framework. *Regional Environmental Change* **2016**, *16*, 1507-1520.
- 248. Haberl, H.; Erb, K.H.; Krausmann, F.; Gaube, V.; Bondeau, A.; Plutzar, C.; Gingrich, S.; Lucht, W.; Fischer-Kowalski, M. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 2007, 104, 12942-12945.
- Krausmann, F.; Erb, K.H.; Gingrich, S.; Haberl, H.; Bondeau, A.; Gaube, V.; Lauk,
  C.; Plutzar, C.; Searchinger, T.D. Global human appropriation of net primary
  production doubled in the 20th century. *Proceedings of the National Academy of Sciences of the United States of America* 2013, *110*, 10324-10329.
- 250. Haberl, H.; Wackernagel, M.; Krausmann, F.; Erb, K.H.; Monfreda, C. Ecological footprints and human appropriation of net primary production: A comparison. *Land Use Policy* **2004**, *21*, 279-288.
- 251. Ma, T.; Zhou, C.H.; Pei, T. Simulating and estimating tempo-spatial patterns in global human appropriation of net primary production (hanpp): A consumption-based approach. *Ecological Indicators* **2012**, *23*, 660-667.
- 252. Running, S.W. A regional look at hanpp: Human consumption is increasing, npp is not. *Environmental Research Letters* **2014**, *9*.
- 253. Sutton, P.C.; Anderson, S.J.; Costanza, R.; Kubiszewski, I. The ecological economics of land degradation: Impacts on ecosystem service values. *Ecological Economics* **2016**, *129*, 182-192.

- 254. Hellden, U.; Tottrup, C. Regional desertification: A global synthesis. *Global and Planetary Change* **2008**, *64*, 169-176.
- Malafant, K.W.J.; Atyeo, C.M.; Derbyshire, P.K. Degradation propensity in australian land tenure systems. *Land Degradation & Development* **1999**, *10*, 455-466.
- 256. Wessels, K.J.; van den Bergh, F.; Scholes, R.J. Limits to detectability of land degradation by trend analysis of vegetation index data. *Remote Sensing of Environment* **2012**, *125*, 10-22.
- 257. McAlpine, C.A.; Fensham, R.J.; Temple-Smith, D.E. Biodiversity conservation and vegetation clearing in queensland: Principles and thresholds. *Rangeland Journal* **2002**, *24*, 36-55.
- 258. Tothill, J.C.; Gillies, C. *The pasture lands of northern australia*; Meat Research Corporation: Brisbane, 1992.
- 259. Friedel, M.H. Range condition assessment and the concept of thresholds. *Journal* of Range Management **1991**, 44, 422-426.
- 260. Ito, A.; Oikawa, T. A simulation model of the carbon cycle in land ecosystems (sim-cycle): A description based on dry-matter production theory and plot-scale validation. *Ecological Modelling* **2002**, *151*, 143-176.
- 261. Lu, Y.; Stocking, M. Integrating biophysical and socio-economic aspects of soil conservation on the loess plateau, china. Part ii. Productivity impact and economic costs of erosion. *Land Degradation & Development* **2000**, *11*, 141-152.
- 262. Knowler, D.J. The economics of soil productivity: Local, national and global perspectives. *Land Degradation & Development* **2004**, *15*, 543-561.
- 263. Stocking, M.; Lu, Y. Integrating biophysical and socio-economic aspects of soil conservation on the loess plateau, china. Part i. Design and calibration of a model. *Land Degradation & Development* **2000**, *11*, 125-139.
- 264. MacLeod, N.D.; Nelson, B.S.; McIvor, J.G.; Corfield, J.P. Wet season resting economic insights from scenario modelling. *Rangeland Journal* **2009**, *31*, 143-150.
- O'Reagain, P.; Scanlan, J.; Hunt, L.; Cowley, R.; Walsh, D. Sustainable grazing management for temporal and spatial variability in north australian rangelands a synthesis of the latest evidence and recommendations. *Rangeland Journal* 2014, *36*, 223-232.
- 266. Eswaran, H.; Lal, R.; Reich, P.F. Land degradation: An overview. *Response to Land Degradation* **2001**, 20-35.
- 267. Lal, R. Soil degradation by erosion. *Land Degradation & Development* **2001**, *12*, 519-539.
- 268. Bai, Z.G.; Dent, D.L.; Schaepman, M.E. *Global assessment of land degradation and improvement: Pilot study in north china 1. Identification by remote sensing.*; ISRIC - World Soil Information: Wageningen, 2008.
- 269. Bastin, G.; Abbott, B.; Chewings, V. Validating a remotely sensed index of landscape leakiness in the burdekin dry tropics, queensland; CSIRO: 2008.

- 270. Ravi, S.; D'Odorico, P.; Breshears, D.D.; Field, J.P.; Goudie, A.S.; Huxman, T.E.; Li, J.R.; Okin, G.S.; Swap, R.J.; Thomas, A.D., et al. Aeolian processes and the biosphere. *Reviews of Geophysics* **2011**, *49*.
- 271. Tanaka, T.Y.; Chiba, M. A numerical study of the contributions of dust source regions to the global dust budget. *Global and Planetary Change* **2006**, *52*, 88-104.
- 272. Holechek, J.L. An approach for setting the stocking rate. *Rangelands* **1988**, *10*, 10-14.
- 273. Lymburner, L.; Dowe, J. *Assessing the condition of riparian vegetation in the burdekin catchment using satellite imagery and field surveys*; Australian Centre for Tropical Freshwater Research (ACTFR): Townsville, 2007; p 74.
- 274. Hutley, L.B.; Beringer, J.; Isaac, P.R.; Hacker, J.M.; Cernusak, L.A. A subcontinental scale living laboratory: Spatial patterns of savanna vegetation over a rainfall gradient in northern australia. *Agricultural and Forest Meteorology* 2011, 151, 1417-1428.
- 275. Hill, M.J.; Roxburgh, S.H.; Carter, J.O.; McKeon, G.M. Vegetation state change and consequent carbon dynamics in savanna woodlands of australia in response to grazing, drought and fire: A scenario approach using 113 years of synthetic annual fire and grassland growth. *Australian Journal of Botany* **2005**, *53*, 715-739.
- 276. Kairis, O.; Karavitis, C.; Salvati, L.; Kounalaki, A.; Kosmas, K. Exploring the impact of overgrazing on soil erosion and land degradation in a dry mediterranean agroforest landscape (crete, greece). *Arid Land Research and Management* **2015**, *29*, 360-374.
- 277. Thackway, R.; Lesslie, R. Vegetation assets, states and transitions (vast):Accounting for vegetation condition in the australian landscape; Bureau of Rural Sciences: Canberra, 2005.
- 278. Fensham, R.J.; Fairfax, R.J. Water-remoteness for grazing relief in australian aridlands. *Biological Conservation* **2008**, *141*, 1447-1460.
- 279. Silcock, J.L.; Fensham, R.J. Arid vegetation in disequilibrium with livestock grazing: Evidence from long-term exclosures. *Austral Ecology* **2013**, *38*, 57-65.
- Bai, Z.G.; Dent, D.L.; Olsson, L.; Schaepman, M.E. Global assessment of land degradation and improvement 1. Identification by remote sensing. Report 2008/01 & glada report #5. ISRIC World Soil Information: Wageningen, 2008.
- 281. UNEP. *World atlas of desertification*. 2nd ed.; Arnold & Wiley, on behalf of UNEP: London & New York, 1997; p 182.
- 282. Ojima, D.S.; Dirks, B.O.M.; Glenn, E.P.; Owensby, C.E.; Scurlock, J.O. Assessment of c budget for grasslands and drylands of the world. *Water Air and Soil Pollution* **1993**, *70*, 95-109.
- 283. Beer, C.; Reichstein, M.; Tomelleri, E.; Ciais, P.; Jung, M.; Carvalhais, N.; Roedenbeck, C.; Arain, M.A.; Baldocchi, D.; Bonan, G.B., *et al.* Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science* 2010, *329*, 834-838.

- 284. Brown, J.; Angerer, J.; Salley, S.W.; Blaisdell, R.; Stuth, J.W. Improving estimates of rangeland carbon sequestration potential in the us southwest. *Rangeland Ecology & Management* **2010**, *63*, 147-154.
- 285. Lal, R. Carbon sequestration in dryland ecosystems. *Environmental Management* **2004**, *33*.
- 286. Ludwig, J.A.; Bastin, G.N. Rangeland condition: Its meaning and use; 2008; p 87.
- 287. Evans, J.; Geerken, R. Discrimination between climate and human-induced dryland degradation. *Journal of Arid Environments* **2004**, *57*, 535-554.
- 288. Li, A.; Wu, J.G.; Huang, J.H. Distinguishing between human-induced and climatedriven vegetation changes: A critical application of restrend in inner mongolia. *Landscape Ecology* **2012**, *27*, 969-982.
- 289. Hutchinson, C.F.; Herrmann, S.M. *The future of arid lands revisited: A review of 50 years of dryland research*. Springer: 2008.
- 290. Cooper, G.F.; Herskovits, E. A bayesian method for the induction of probabilistic networks from data. *Machine Learning* **1992**, *9*, 309-347.