A transdisciplinary evaluation of forest retention policies and practices in the Australian context

PhD Thesis submitted by

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Hernandez, S Barnes, M., Adams, VM., Duce, S. 2020 "*Do protected areas prevent deforestation in a global deforestation hotspot?*" Scientific Reports[2]

Papers in preparation

Hernandez, S Sheaves, M. Murray, N. Adams, VM, Duce, S. 2020 "The use of ex-ante evaluation to identify priority areas for conservation." Conservation Biology[3]

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Hernandez S. (2019, July) "*Do protected areas prevent deforestation in a global deforestation hotspot?"* Association for Tropical Biology and Conservation. Antananarivo, Madagascar

Hernandez, S. (2019, May) "*How can publicly available data be used to inform decision-making?*" Pint of Science. Townsville, Australia

Hernandez, S. (2018, July) "*Do protected areas prevent deforestation in a global deforestation hotspot?"* Society for Conservation Biology -Oceania. Wellington, New Zealand

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Hernandez S. 2019 "*Species distribution models for 9,565 native plants in Queensland"* Internal Report for the Department of Environment and Science.

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Statement of the contribution of others

In Chapter 1, I introduce the historical and research context and policy settings which underpin the foundation of this thesis. I gratefully acknowledge Graham Lake and others at the Queensland Government for the provision of historical gazette notices which document Queensland's first National Parks. I wrote this chapter with editorial and structuring assistance from Stephanie Duce and Claudia Benham.

In Chapter 2, I introduce the policy context for protected areas in Queensland. I Identify and discuss how key themes relating to drivers of protection are represented in Australia. I conceived and wrote this chapter, with editorial and structuring assistance from Stephanie Duce, Claudia Benham and Marcus Sheaves. Peter Johnson provided expert contribution in terms of describing protected area policy.

In Chapter 3, I describe and complete a robust impact evaluation of the current strictly protected area network. In this context, an impact evaluation refers to the directly attributable difference protection has made in terms of preventing forest loss. Vanessa Adams originally conceived this project, I designed, implemented and wrote this chapter. I created all figures and content in this chapter except for **Figure 3-2**, which was created by Megan Barnes. Comments, edits and structuring support were provided by Megan, Vanessa and Stephanie Duce, Linda Lee and Peter Johnson. I also thank Brett Kerr, who provided reviews of this work which significantly improved the manuscript.

Chapter 4 builds on work completed in my Master's thesis at James Cook University. For that project, I created spatial data layers per the Department of Natural Resource, Mines and Energy's vegetation clearing guidelines. In work presented here, I reanalysed this data for summaries that clearly describe variations in the compliance requirements for three variants of clearing guidelines. This analysis allows for a State-wide decision-making resolution and describes the rapidly changing differences in specific policy directives. I conceived the idea and created all the figures. I received structuring and editing assistance from Robert Pressey, Vanessa Adams and Megan Evans. I gratefully acknowledge Land Officers at the Department of Natural Resources and Mines who validated my interpretation of the clearing guidelines. I also acknowledge Bruce Wilson for his valued expert advice on regional ecosystem mapping and environmental impact assessment.

In Chapter 5, I identify priority areas by combining habitat status with the probability of deforestation layers. The idea for this project was conceived by Peter Johnson, Brad Ellis, and myself. This chapter represents a novel approach to sophisticated statistical modelling to maximise avoided loss and was ultimately successful because of the valuable expertise involved. I created the probability of deforestation layers and received advice from Oyelola Adegboye on experimental design and testing for model fit. I also received coding assistance from Erin Graham. Acknowledging these contributions, I designed the analysis for this chapter, created all figures and wrote this chapter, with editing assistance from Stephanie Duce, Nicholas Murray and Marcus Sheaves.

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"You change your laws and your administering of them so fast, and without inquiry after results past or present, that it is all experiment, seesaw, doctrinaire; a shuttlecock between battledores."

– Florence Nightingale (1924)

Thesis Abstract

Environmental changes caused or influenced by human activity have increased the current rate of extinction to 100-1000 times the standard background rate (Ceballos et al. 2015). The reduction or loss of habitat for conversion to extractive uses, urban development or resource production causes environmental change and is considered a key threat to the suite of values associated with intact forests (Kingsford et al. 2009). Important mechanisms for abating species decline in the face of such pressures include protected areas and vegetation management policy. Globally, protected area expansion is exponential (Steffen et al. 2011) and yet studies that test the effectiveness of protected areas in achieving biodiversity outcomes remain rare (Schleicher, Eklund, D. Barnes, et al. 2019). This is highly problematic because a lack of evaluation undermines society's ability to address emergent declines in biodiversity or ecological integrity, and to adapt policy responses accordingly.

Commonly adopted targets relating to the simple area of a region or representation of species or communities, are easy to count for reporting purposes but may be achieved with little value in terms of avoiding the loss of biodiversity. As previous studies have shown, strict adherence to these targets without a deep understanding of ecological and conservation science may threaten *bona fide* progress in terrestrial conservation because resources for nature conservation are limited and increasingly disproportionate to the magnitude of biodiversity loss. It is of the utmost importance to effectively prioritise conservation policies and programs to maximise the efficiency of limited funding. A failure to maximise the efficacy of programs and policies is problematic not only in terms from a scientific perspective but also because failing to adequately control threatening processes can have a disastrous impact on biological diversity and ecological integrity.

Effectively designing policies and programs requires a deep understanding of social, cultural, economic and political values. This thesis contributes to filling gaps in political and socio-economic values by evaluating the effectiveness of policy responses to deforestation in Australia, a global deforestation hotspot (Cresswell and Murphy 2017).
The goals of this thesis are to:

1) review policies and programs for retaining natural forested habitats in Australia;
2) estimate the impact of current protected areas in terms of preventing forest cover loss;
3) describe the impact of policy changes on vegetation;
4) develop evidence-based recommendations for retaining Queensland's forests in the future.

Owing to complex governance arrangements for forest retention policies and programs, I use a transdisciplinary mixed-methods approach to investigate the complexities, effectiveness and future directions for conservation policy in Queensland, Australia. I combine rigorous qualitative policy analysis

(**Chapters 2 and 4**) with robust quasi-experimental evaluation methods (**Chapters 3**) and frequentist modelling (**Chapter 5**) to produce policy-ready recommendations for the future security of Queensland's native forests (**Chapter 6**).

In my first chapter, I set the scene for the relevance of this work by broadly introducing the primary mechanisms for forest retention (protected areas and environmental impact assessment). In developing this chapter, it became clear that the Australian state of Queensland is characterised by high rates of clearing, low rates of formal protection and globally significant biodiversity. These characteristics make Queensland an ideal case study for evaluating the effectiveness of deforestation mechanisms. To do this, however, there is a clear need to understand how protected areas are established across Australia. That is, what are the fundamental principles which drive gazettal. In Chapter 2, I use thematic analysis to identify and describe these principles as they occur in Australian policy documents. I found that representativeness was the most common driving principle for protected areas. Representativeness refers to ensuring that each type of ecosystem is contained within a reserve network. Given Queensland's high rates of clearing (established in Chapter 1), however, is it logical to consider the feasibility of meeting a representativeness target as ecosystems are increasingly threatened with extinction. The next logical question, then, is whether or not protected areas effectively reduce clearing. The aim of Chapter 3 is to assess Queensland's protected area network for impact retrospectively. This establishes counterfactual scenarios to provide a robust estimate of the relative impact of Queensland's protected area system. I found that the majority (89.5%) of strictly protected areas would not have been cleared even in the absence of protection. This means that protection made no difference to deforestation in these areas.

It is equally important to understand how regulation which relates to vegetation management contributes to *de facto* protection. An area is considered to be *de facto* protected if policy interventions prevent or significantly limit clearing. In this context, the relevant policies are guidelines which support Queensland's *Vegetation Management Act, 1999* (the Act). In Chapter 4, I evaluate the spatially explicit criteria for each guideline, summarise and then describe policy changes, including those which result in *de facto* protection. I found that the majority of Queensland's vegetation does not have spatial features which would trigger an assessment under the Act.

Australia's significant and mostly endemic biodiversity is in long-term decline. The single most significant factor which can be attributed to continued species decline is habitat loss as humans increasingly modify natural environments. The results of the Chapters described above suggest that the mechanisms for retaining forested habitats in Queensland could be bolstered by understanding potential future scenarios of land clearing. These future scenarios can be a critical guide for strategic directions by anticipating opportunities to avoid the loss of high-risk areas.

In Chapter 5, I used a generalised estimating equation to predict deforestation in Queensland's forested bioregions. I then combined these models with vegetation community mapping in Queensland and calculated which communities were likely to migrate into a higher vulnerability status (*ie* a least concern community becoming endangered). Using scenarios which constituted the projected severity of land-clearing, I identified between 29 and 212 communities are likely to increase in their vulnerability status. Of these, between five and 20 communities are likely to go extinct if no action is taken. To prevent such loss, it is imperative that policy intervention target areas with high vulnerability to future loss.

Recommendations for these targeting areas with a high vulnerability to future loss are provided in the final chapter (Chapter 6). I build on the information developed in the first five chapters of this work to provide recommendations which link conservation outcomes to biodiversity threats and the types of decisions required of governments to maximise impact. To ensure that these recommendations are practical and feasible, I have worked closely with decision-makers throughout this project. This collaboration ensures the policy relevance of the work useful while also maintaining robust scientific methods. By achieving the objectives listed above, my thesis provides an essential contribution to future protected area policy and the academic literature concerning conservation planning by assessing current forests retention mechanisms and providing strong recommendations for policy.

Thesis Keywords:

Deforestation, evaluation, protected areas, assessable vegetation, public policy, biodiversity conservation, environmental governance, environmental regulation, mixed methods, interdisciplinary research

Glossary

TERM	DEFINITION
Assessable vegetation	Vegetation which contains spatial features controlled by public policies of the Vegetation Management Act,1999 (the Act). It is important to note that this is a separate and distinct definition from regulated vegetation as per the Act itself.
Bioregions	Specific geographic regions which are designated, managed and regulated to achieve conservation actions.
Confounding	The variables that influence a site's likelihood of being protected or cleared
Counterfactuals	Statistically similar control sites used as proxies in quasi-experimental designs
Co-variates	For this thesis, confounding variables (see above) are known as co-variates.
Department of Environment and Science (DES)	A branch of Government responsible for managing environmental and heritage values and assets in Queensland.
Environmental Impact Assessment (EIA)	Environmental impact assessments are systematic appraisals of the intended or unintentional consequences of development or extractive activity on environmental features or values.
Exchange area	An area of vegetation that must be protected in exchange when clearing above specified limits or in sensitive areas.
High-value regrowth	Vegetation located: (a) on freehold land, indigenous land, or the land subject of a lease issued under the Land Act 1994 for agriculture or grazing purposes or an occupation licence under that Act; and (b) in an area that has not been cleared (other than for relevant clearing activities) for at least 15 years, if the area is: (i) an endangered regional ecosystem; or (ii) an of concern regional ecosystem; or (iii) a least concern regional ecosystem.

TERM	DEFINITION
Non-remnant regional ecosystems	Areas that are not remnant vegetation or high-value regrowth vegetation. Generally, these are areas that have been cleared and contain limited amounts of native vegetation such as built-up areas or pastures. However, in some circumstances, it may contain some limited regrowth regional ecosystems that have been cleared after 31 December 1989.
Pre-clear regional ecosystems	The vegetation or regional ecosystem present before clearing. This generally equates to terms such as 'pre-1750' or 'pre-European.'
Regional Ecosystems	The distinctive vegetative communities, remnant and regrowth, classified by bioregion, dominant flora species, landform, and geology (Neldner et al. 2005).
Remnant regional ecosystems	Vegetation that has not been cleared or vegetation that has been cleared but where the dominant canopy has greater than 70% of the height and greater than 50% of the cover relative to the undisturbed height and cover of that stratum and is dominated by species characteristic of the vegetation's undisturbed canopy
Regulated Vegetation	Queensland's Vegetation Management Act, 1999 refers to categories of vegetation (*ie* A, B, C, R or X; Appendix 4) as "*regulated.*"
Regional Ecosystem's Vegetation Management Status	
Endangered	For woody vegetation, regional ecosystems with: 1. The dominant canopy having greater than 70% of the height and greater than 50% of the cover of values in undisturbed vegetation; and 2. Dominant species are characteristic of the vegetation's undisturbed* canopy. For non-woody vegetation, regional ecosystems mapped by the Queensland Herbarium as not cultivated since 1989. An undisturbed canopy shows no evidence of extensive mechanical or chemical disturbance (logging, clearing, poisoning) as evident in field inspections or aerial photographic record. Remnant vegetation in regional ecosystems with: 1. Less than 10% of their pre-clearing extents remaining, or

TERM	DEFINITION
	2. 10–30% of their pre-clearing extents remaining and the remnant vegetation covering less than 10,000ha, or 3. Less than 10% of their pre-clearing extents remaining unaffected by severe degradation and biodiversity loss, or 4. 10–30% of their pre-clearing extents remaining unaffected by severe degradation and biodiversity loss and the remnant vegetation covering less than 10,000ha, or 5. Classification as rare or subject to a threatening process
Of-Concern	Remnant vegetation in regional ecosystems with: - 10–30% of the estimated mapped extent before European settlement remaining; or - more than 30% of the estimated mapped extent before European settlement remaining and the remnant extent less than 10,000 ha, or 10–30% of the estimated mapped extent before European settlement remaining unaffected by moderate degradation and biodiversity loss.
Least Concern	Remnant vegetation in regional ecosystems with: 1. More than 30% of their pre-clearing extents remaining, and remnant area greater than 10,000 ha, or degradation criteria listed above for 'endangered' or 'of concern' are not met.
Other Vegetation Categories	
At-Risk Regional Ecosystems (2013)	Vegetation which is in danger of falling below 30% of the estimated mapped extent before European settlement.
Dense Regional Ecosystems (2013)	The percentage foliage cover of 70-100% (Specht 1970).
Essential Habitat	Areas wherein a species (such as a plant or animal) listed as conservation concern under the Nature Conservation Act (1992) is known to occur in that area.

Chapter 1. Introduction

1.1 Deforestation: a growing threat

Covering roughly one-third of Earth's landmass, forested habitats are indispensable as they support exceptional environmental and social values (Fritz-Vietta 2016). In addition to being one of the most biologically diverse terrestrial environments (DeAngelis 2008, FAO 2010), forests also play a crucial role in climate change mitigation. For example, recent estimates suggest that forests absorb one-third of annual carbon dioxide emissions released from fossil fuels and contributing to a healthy atmospheric balance of oxygen, carbon dioxide and humidity (Reich 2011). Furthermore, more than 1.6 billion people rely on forests for their daily subsistence needs (Ghimire and Pimbert 1997).

Despite these values, forests are imperilled by expanding human consumption of natural resources. Such activities, directly and indirectly, cause deforestation. While natural events such as cyclones and fires can cause temporary forest cover loss or diminution, deforestation by land clearing, is defined as '*the outright and permanent removal of previously forested land to non-forested land'* (Myers 1991). Deforestation is caused by socio-economic demands and has significant implications for biodiversity and ecosystem function (Gibson, McKean, and Ostrom 2000, Jha and Bawa 2006). Recent figures suggest that 177,000 km^2 of forested areas are cleared per year (roughly the size of Cambodia) (World Wildlife Fund 2017). As forests are cleared, valuable ecosystem services and important carbon sinks are destroyed.

The first ideas about strategic landscape planning for high-value forested landscapes emerged in the late 1980s, driving policy directives and resourcing for landscape protection (Sloman 2005) (Ahern 1999). In parallel, researchers provided the world with typologies of deforestation processes and drivers (Allen and Barnes 1985). Such research is useful in developing causal deforestation models to inform policy decisions. Causal modelling has attracted significant global attention because models can be useful in making decisions around where to buy land for conservation and where to expand commercial or economic interests (Meyfroidt 2016). Consequently, causal deforestation modelling and evaluations of deforestation management tools can function as a decision-support tool by critically answering the question "what would have happened if we did nothing (Sloman 2005)?" These types of robust evaluations can help ameliorate land-use conflict and support management decisions by predicting land-use change to inform management and conservation initiatives.

1.2 Policy tools for habitat retention

It is well-understood that competing interests drive land-use conflict (Lemly, Kingsford, and Thompson 2000, Niemelä et al. 2005, Hirsch et al. 2011, Tscharntke et al. 2012). The retention of habitat for the benefit of ecosystems and biodiversity is an expensive (Hoffmann and Broadhurst 2016), and value-laden enterprise (Harding 2006, Humphreys 2012) and differences in these values present an enormous challenge for developers, public authorities and members of the public. In addition to local government by-laws and planning schemes, value differences, in terms of the retention of intact habitats, are primarily negotiated with two main pathways: the declaration of protected areas and restrictions on development via the vegetation management process.

Policies are developed in response to positions taken because of a recognised problem and include actions for its resolution (Dovers and Hussey 2013). There are different types of policies, each of which operates at either national, state, local (*ie* council or local Government), or institutional. Elected officials create *legislative* policies, and these are typically referred to as laws or ordinances. *Regulatory* policies are created by regulatory authorities (such as government bodies) and include rules, guidelines or principles. *Institutional* policies are established within an agency or organisation and include rules and practices (Freeman 2013). Policies can be an effective ways to create positive changes concerning biodiversity and biodiversity assets, and these changes can be achieved by setting strategic targets in regulatory policies.

1.2.1 Protected areas

Increasing human expansion and consumption has resulted in increased demands for land and natural resources, compounding the processes which threaten the persistence of species. Protected areas are one mechanism for abating species decline considering these pressures. The IUCN definition of a protected area is a defined geographical location that is legally dedicated and managed to achieve long-term nature conservation and maintain associated cultural values and ecosystem services (Dudley et al. 2010). Protected areas are managed for biodiversity outcomes and, for this reason, anthropogenic activities which are known to negatively affect species are generally prohibited from these areas (**Appendix 1**). Protected areas, therefore, are a fundamental tool for securing biodiversity, and, when correctly applied, can halve species' extinction risks (Di Marco et al. 2019) and provide critical areas for species' population recovery (Watson et al. 2010).

1.2.2 Vegetation management policies

Legal obligations to conserve natural heritage are addressed at multiple governance levels through primary legislation and their supporting regulations and policies (Europe 1991, Brodhag and Talière 2006). Generally, the systematic appraisal of potential intended, and unintended consequences of development is occurs within the broader legal regulation of vegetation (Boulter et al. 2000). Ultimately, these processes are constrained by the qualitative judgements required to assess the many impacts of a project (Peirce, Weiner, and Vesilind 1998, Wilkinson 2015). Previous studies voiced concerns about the functional weaknesses such process because of the bureaucratic methods of obtaining development approval (Brown and Hill 1995). Specifically, because a conflict of interest may be intrinsic to most development assessments when the proponent is also the regulator (Grech et al. 2013). Such may be the case in Queensland's vegetation management framework (Moon 1998) when a seemingly comprehensive process has proved ineffective at preventing or reducing deforestation (Simmons, Wilson, et al. 2018). In order to improve vegetation management pertinent procedures, aimed at minimising and preventing loss are of paramount importance.

1.3 Global targets and systematic conservation planning

In 1992, the Australia became signatory to the Convention on Biological Diversity (CBD) - one of the most highly supported international environmental agreements (CBD Secretariat 2016). The CBD requests countries to establish a system of protected areas and guidelines for their selection. These guidelines, know as the "Strategic Plan" or "Aichi Targets" have the purpose of inspiring broad-based action in support of biodiversity and measuring progress against this action (Woodley et al. 2012). Under this convention, Australia agreed to develop a system of protected areas with the purpose of "[securing] long-term protection for samples of all our diverse ecosystems and the plants and animals they support (Australian Government 2012)." In doing so, the Federal government furthered area targets by committing to the development of a national, comprehensive system of parks and reserves. With the agreement of all nine states and territories, a cooperative program for reserve selection and sustainable management was developed. This program is known as the Regional Forest Agreements (RFAs) and, in addition to establishing a series of other principles around resource access and sustainable development, also established the principles of comprehensiveness adequacy, and representativeness (CAR) (TFMPA 1999b, a, Commonwealth of Australia 1997b, Thackway and Cresswell 1995a). The CAR principles were adopted based on internationally accepted theories on systematic conservation planning (Kukkala and Moilanen 2013, Possingham, Wilson, Andelman, and Vynne 2006, Margules and Pressey 2000b).

Appropriately designating land for protection is both a time and resource-intensive process, and, given imminent and increasing threats to biodiversity, both are limited. Thus, researchers and practitioners face the same question: Where should conservation efforts be focused to effectively and efficiently halt biodiversity loss. To answer this question, systematic conservation planning was developed in the early 2000s (Margules and Pressey 2000b). Systematic conservation planning was quickly incorporated into academic (Álvarez-Romero et al. 2018) and industry planning exercises. Systematic conservation planning is a multi-disciplinary exercise purposed with providing cost-effective advice for securing the highest representation of biodiversity through the creation of robust conservation targets. Conservation targets are explicit goals which quantify the minimum extent of a species, vegetation type, or other biodiversity feature to conserve through one or more conservation actions (Possingham, Wilson, Andelman, Vynne, et al. 2006).

While the popularity of systematic conservation planning has grown over steadily in the 36 years that followed its development, there are strict limitations and warnings regarding its application. For example, planning must be contextually appropriate considering such elements as stakeholder groups, governance and biophysical subsystems (Adams et al. 2019, Pressey et al. 2013) as well as targeted at a specific problem. Furthermore, despite the increasing application of systematic conservation planning at global and local levels, (Adams et al. 2019), there is little empirical evidence of the success of conservation efforts in terms of avoided loss of biodiversity (Barnes et al. 2018b). Some authors have argued that the limitations of target-based conservation planning lie in poor communication and the misuse of targets (Carwardine et al. 2009). Other authors suggest that setting conservation targets are ultimately detrimental to biodiversity because societies can use targets as justification to destroy untargeted biodiversity features (Traill et al. 2007). Despite these concerns, the scientific literature suggests that conservation targets are best practice, thus warranting an evaluation justifying their role in conservation planning in Australia (Conservancy and Fund 2006).

Despite the benefits of well-designed protected areas, there is a global tendency for protected areas to be located on lands which are unproductive or not useful for commercial purposes (Joppa and Pfaff 2009). In the scientific literature, this is known as "*residual bias* (Vieira, Pressey, and Loyola 2019)." Residual bias is thought to be caused by policies (implicit or explicit) which seek to minimise opportunity costs to commercial or extractive land-use stakeholders (Devillers et al. 2015). One significant consequence of residual bias is that species and ecosystems which most urgently require protection become even more vulnerable to extinction (Pressey, Visconti, and Ferraro 2015). Importantly, biodiversity in more heavily used and threatened areas differs from that in less used and less exposed areas. Differences in biodiversity composition arise from both physical and geographic variation and the modification of natural environments. So, exploited and the unexploited regions tend to be biologically distinct (Australia; State of the Environment Committee 2011). If protected areas are acquired with an aim to reduce or minimise opportunity costs for extractive use stakeholders, there are two potentially perverse outcomes. First, protection avoids the areas which are more costly in terms of the opportunity for extraction, and, second, protection is not afforded to biodiversity which most urgently requires protection. The risk of perverse outcomes is significantly reduced when explicit objectives and goals are designed at the policy level (Adams, Barnes, and Pressey 2019).

1.4 Policy evaluation

In general, public policies are deliberate, documented decisions which are representative of the Government or other political actors. The purpose of a policy is to influence, change or frame a problem or public issue (Hassel 2015). A growing field of research in social, biomedical and behavioural sciences is the field of program and policy evaluation which study how effective an intervention is at achieving its desired outcome. In the context of this field, the interventions studied are often government programs or, more generally, any intervention of interest by public or private agents (Abadie and Cattaneo 2018).

Policy evaluation was defined by David Nachimas (1979) as the "*objective, systematic, empirical examination of the effects ongoing policies and public programs have on their targets in terms of the goals they are meant to achieve.*" Thus, evaluation refers to the systematic method for collecting, analysing and assessing information project or policy effectiveness concerning its stated goals. Evaluation is separate from program monitoring and assessment because it requires a comprehensive definition of the problem addressed by the policy, including a detailed understanding of the context (Salafsky and Margoluis 1998), an assessment of the performance, and the dissemination of findings and recommendations to appropriate stakeholders. Evaluations are useful for providing public and internal accountability to help demonstrate impact (Hockings, Stolton, and Dudley 2000) by answering questions relating to performance and identifying conditions or constraints likely to cause the strategy to falter (Hatry 2006). Evaluation is, therefore, an essential component of functionality within the context of policies and programs because it facilitates feedback along the entire chain of the policy process (**Figure 1-1**).

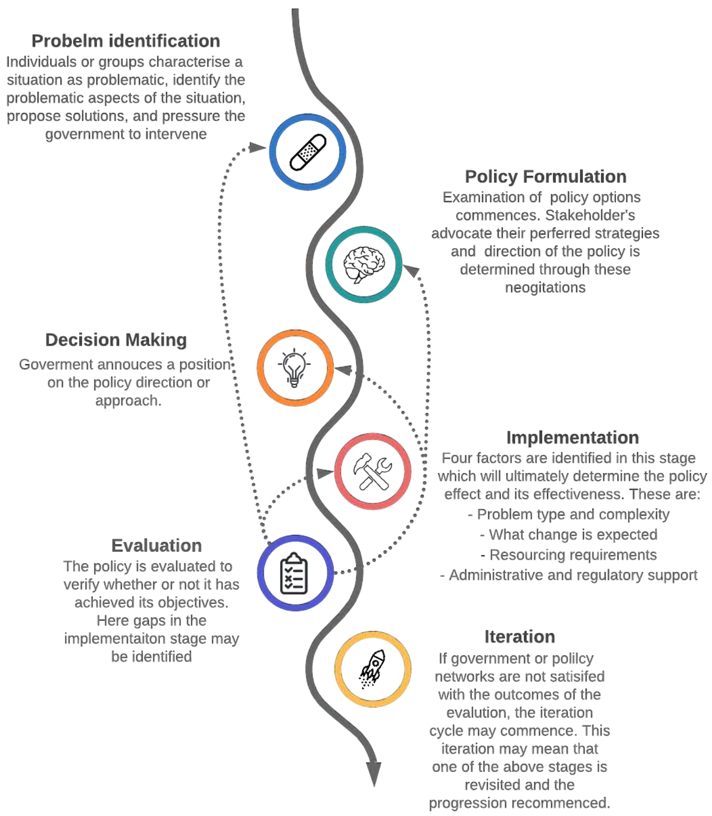


Figure 1-1: Six stages of the policy process. It was adapted from (Althaus, Bridgman, and Davis 2013).

While numerous approaches are available to researchers, decisions around which policy evaluation model to adopt centres broadly around three questions: Do we need to know how the policy operates *in situ* (termed process evaluation), Do we need to know what the impact of the policy was in terms of achieving its desired outcomes (termed ex-post or impact evaluation (Purdon et al. 2001))?; or do we need to know how well a policy will perform before it is implemented? (termed ex-ante evaluation, (Todd and Wolpin 2008)). In this thesis, I focus on ex-post and ex-ante evaluation. Central to both evaluations is a consideration of the counterfactual. Counterfactuals are required to effectively quantify the change in the relationship of informative predictors with the outcome because of an intervention (such as a policy) because they control for confounding. For example, researchers might be interested in evaluating the effectiveness of clearing a hazardous waste site on housing prices (Stock 1991), how labour surplus effects the rural-urban income gap (Cai and Wang 2008), how income inequality impacts social mobility (Cunha, Heckman, and Navarro 2006) or how gang membership impacts nonviolent and violent delinquency (Barnes, Beaver, and Miller 2010). In each of these situations, the underlying trends in housing prices, labour availabilities, income gaps and delinquency rates must be understood. In doing so, researchers compare two states of the world: the world in which the intervention occurred, and the world in which the intervention did not occur. The second world is the counterfactual world and allows researchers to quantify how much difference was made because (and only because of) of the intervention being studied.

Randomised control trials are considered to be the gold-standard in evaluating the counterfactual outcome (Pynegar et al. 2019), but such a study would require both randomly allocating protected and unprotected areas across regions and jurisdictions and commencing an evaluation at the time of their establishment. In the context of protected areas, however, they are often located land which is unsuitable for commercial extractive activities (*ie* steep slopes and low productive capacity (Joppa and Pfaff 2009, Pressey et al. 2002, Miranda et al. 2016). Protected areas in such locations are unlikely to be cleared in the first place and evaluation methods which fail to account for this may overestimate the impact of protected areas (Andam et al. 2008, Pfaff et al. 2009). Because protected areas tend to be long established, researchers and practionioners are faced with the fundamental problem of causal inference: it is impossible to observe what would have happened to protected areas in the absence of protection (Holland 1986). There are a range of study designs aimed at addressing this problem (Jones and Lewis 2015, Barnes et al. 2016, Stuart 2010, Stuart and Rubin 2008), and quasi-experimental evaluation designs, including statistical matching, are a robust approach (Stuart and Rubin 2008, Kirk 2007, Blackman 2013, Jusys 2018). Statistical matching methods resemble a randomised experiment and are designed to support policy evaluation (Adams, Barnes, and Pressey 2019). Matching uses statistical techniques to 'match' protected sites with unprotected (control) sites that are as similar as possible to protected sites. Similarity is derived from variables that influence either their likelihood of being protected or of being cleared. Such an approach requires rigorous identification of a counterfactual (or statistically similar control), and quantifying change as a result of the treatment (protection). The variables that influence a site's likelihood of being protected or cleared are called "*confounding variables*." For example, land on steep slopes is more difficult or costly to clear, thereby constraining clearing to land with lower slopes. Here, I refer to confounding variables as "*co-variates*." Statistically similar control sites based on these co-variates are referred to as "*counterfactual'* areas, and they are used as a proxy to estimate the otherwise unobservable conservation outcomes of protected areas if they had not been protected.

In environmental and conservation literature, robust impact evaluation of conservation initiatives which consider these counterfactuals, have become increasingly called for over the last decade (Ferraro 2009, Ferraro and Pattanayak 2006, Pattanayak, Wunder, and Ferraro 2010, Pressey, Visconti, and Ferraro 2015), but remain rare in the conservation literature (Pattanayak, Wunder, and Ferraro 2010, Baylis et al. 2015, Ferraro 2009, Schleicher, Eklund, et al. 2019b). In a climate of budgetary constraints, are pivotal tools for informing decision-makers about how well their conservation investments are performing, thus informing multiple stages of the policy process. This thesis contributes to filling gaps in political and socio-economic values by using robust mechanisms for evaluating the effectiveness of policy responses to deforestation in Australia, a global deforestation hotspot (Cresswell and Murphy 2017).

The goals of this thesis are to:

1) review policies and programs for retaining natural forested habitats in Australia;
2) estimate the impact of current protected areas in terms of preventing forest cover loss;
3) describe the impact of policy changes on vegetation;
4) develop evidence-based recommendations for retaining Queensland's forests in the future.

1.5 Deforestation: Queensland as a case study

Australia is the world's driest inhabited continent with a nutrient-poor landscape (Lindsay 1985). Despite its harsh climate and low soil fertility, Australia is considered a mega-diverse country with unique biodiversity arising from its long evolutionary separation from Gondwana (Steffen 2009). Australia is home to between 600,000-700,000 native species, many of which are endemic (The Department of the Environment and Energy. ND). Human-induced environmental change, including species decline and extinction, has been occurring in Australia since the first arrival of humans (~50,000 BCE) (Miller et al. 2005) but has accelerated following European settlement with the introduction of European agricultural practice. Since 1972, nearly 17 million hectares of primary and regrowth vegetation has been cleared in Australia for development, urbanisation, and agricultural or pastoral production (Evans 2016, McAlpine et al. 2009). The environmental consequences of poor land management practices in Australia have led to the introduction of environmental legal systems purposed with securing biodiversity and environmental quality. The structure and effectiveness of these legal systems are highly significant as Australia faces new and ongoing environmental issues (Hobday and McDonald 2014).

In Australia, there are five levels to the environmental legal system: international law, Commonwealth (Federal) law, State Law, local government by-laws and common law (McGrath 2003, Bates and O'Shea 1992). International law is created by the collective actions of individual nations and is enforced by the nations party to the assembly. For example, the *Convention on the international trade of endangered species of wild fauna and flora 1973* (CITIES) provides a framework for controlling the international trade of more than 30,000 species of plants and animals. International law has significant constitutional ramifications for the Australian Federal and State governments, as explained in the next sections. Local government by-laws are created by local governments to meet individual and specific community needs. Common law pertains to the law created by judicial decisions which set a precedent for future decisions. Common law relevant to environmental matters may include such things as private and public nuisances, watercourse rights, negligence and trespassing (Bates and O'Shea 1992), but do not directly relate to forest retention and are therefore not discussed further.

The centrepiece of the Commonwealth (Federal) environmental legal system is the *Environmental Protection and Biodiversity Conservation Act, 1999* (EPBC). The EPBC provides the framework to manage and conserve internationally and nationally significant plants, animals, ecological communities and heritage areas. Activities that are likely to significantly affect the values of these assets require approval from the Australian Government. Federal legislation is upheld by guiding frameworks or strategies. These include such things as *Australia's Biodiversity and Conservation Strategy 2010-2030* and *The Australian Government's Threatened Species Strategy.*

The regulation of these environmental matters occurs primarily at the State and Territory level. Particularly important State law in Queensland, relating to vegetation management and protected areas include the *Sustainable Planning Act,* 2009, the *Environmental Protection Act 1994,* the *Nature Conservation Act* 1992 and the *Vegetation Management Act 1999 (Boer and Gruber 2010).* Each of these acts is supported by individual policies and regulations and will be described in greater detail throughout this thesis. I begin, however, by describing the history of protected areas in Queensland as this sets the political context for forested habitats in the State. A description of the methods used in this historical review is provided in Appendix 1.2, **Figure 1-2.**

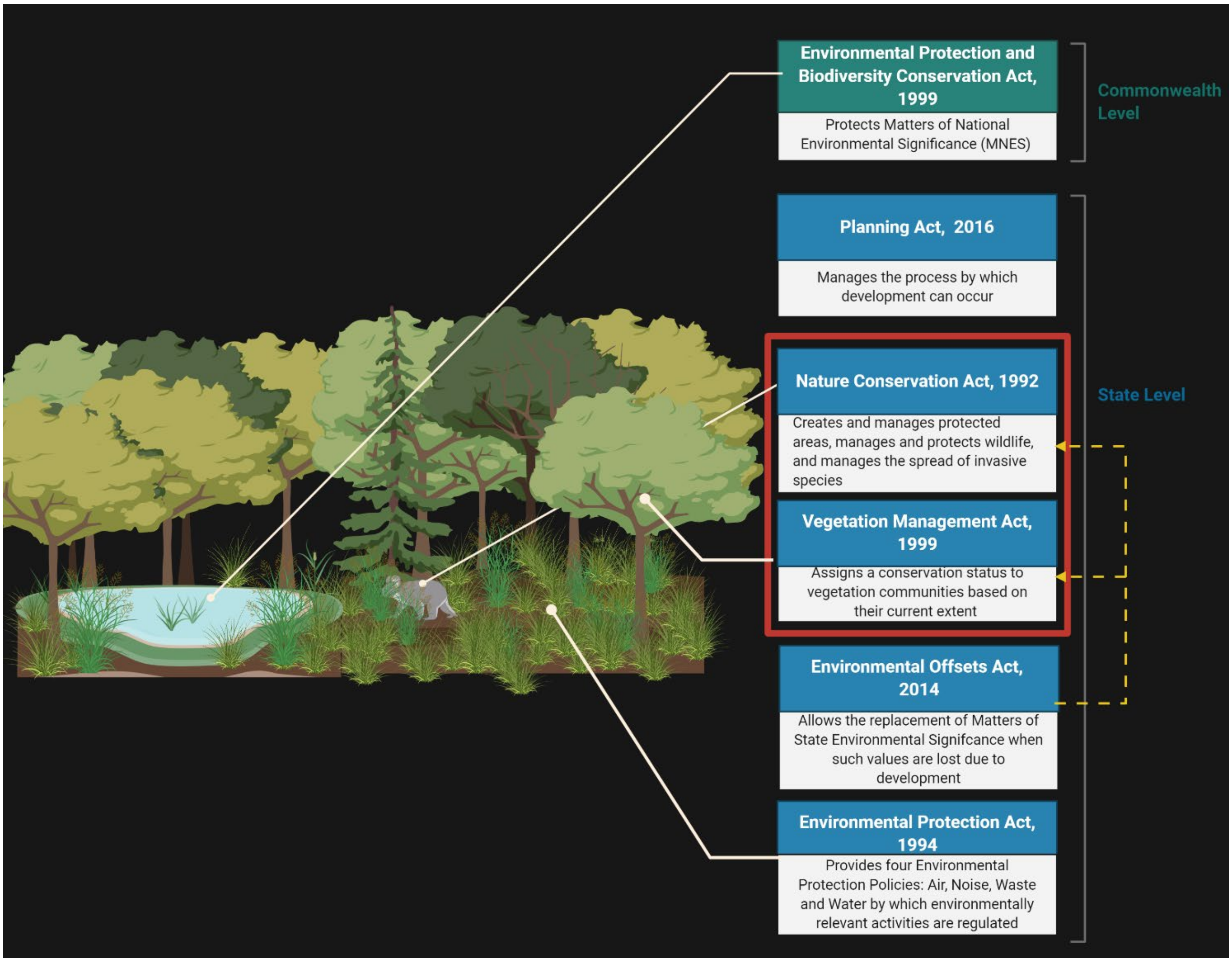


Figure 1-2: Schematic representation of the primary Federal and State legislation for maintaining biodiversity and the environment in Queensland. The Environmental Offsets Act regulates Matters of State Environmental Significance (MSES) which are indicated in the Vegetation Management Act 1999 and the Nature Conservation Act 1992. In this thesis, I focus on the regulations and policies supported by these two Acts.

Environmental changes caused or influenced by human activity have increased the current rate of extinction to 100-1000 times the standard background rate (Ceballos et al. 2015). The reduction or loss of habitat for conversion to extractive uses, urban development or resource production is a significant threat to biodiversity (Kingsford et al. 2009). In Australia (Evans 2016), and particularly in Queensland (Bradshaw 2012), there has been a persistent and gradual reduction in native forest cover as a result of human activities.

Since 1972, 16.7 million hectares of forests were cleared across Australia. The majority (58%) of land clearing in Australia has occurred in the State of Queensland (**Figure 1-3**) (Bradshaw 2012, Evans 2016). For example, in the four years between 1991 and 1995, Queensland was responsible for 80% of the 1.2 million ha cleared across Australia (Accad and Neldner 2015, Wilson, Neldner, and Accad 2002). Between 2001 and 2003, clearing of woody vegetation in Queensland reached levels of over 1.05

million ha per year (0.56% of Queensland's total area). Indeed, Queensland's historical and current rate of land clearing has earned the state the title of a global deforestation hotspot. While the continued persistence native species are threatened by several factors including climate change, disease, invasive species and pests, the most significant threat impacting species viability is accelerated habitat degradation and loss (Bradshaw 2012).

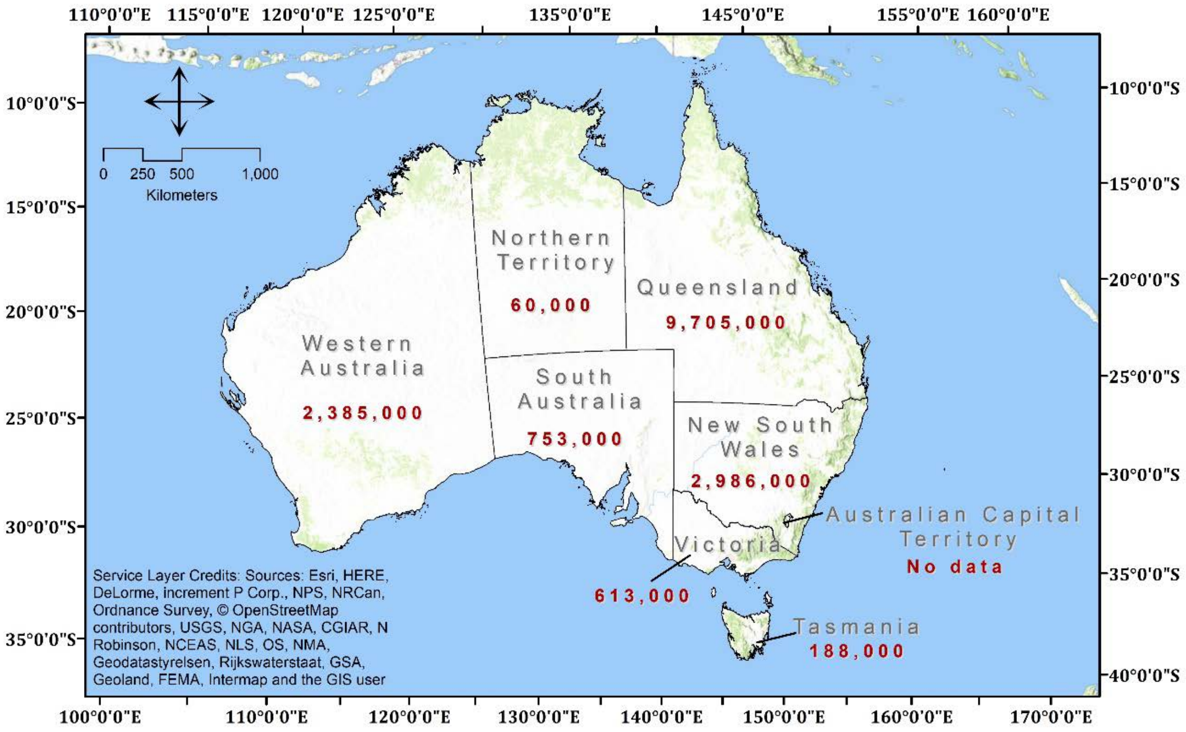


Figure 1-3: Total (primary and regrowth) amount of deforestation (ha) for each state and territory from 1972-2014. Data were sourced from the Australian Government's State of the Environment Report (Metcalfe and Bui 2017).

Queensland, in line with international strategies, has agreed to conserve biodiversity through a robust and effective protected area network (Queensland Government. 2017) and sound vegetation management regulations. Currently, Queensland's protected area network covers just over 8% of the State's land area; however, there are Government commitments to increase the land in protected areas to 17% of the State. The extent to which Queensland's protected areas combat deforestation by avoiding habitat loss is unknown. Furthermore, recent overhauls to vegetation management which reduced restrictions around land-clearing have had severe consequences for biodiversity.

Queensland's clears more woody vegetation than the combined total of all other Australian States and Territories (**Figure 1-3**). At a rate of nearly 400,000 ha per year, Queensland is described as a global deforestation hotspot (Reside et al. 2017). Queensland, therefore, requires urgent and significant actions to secure the persistence of its highly endemic biodiversity. To combat deforestation pressure, Queensland has developed key policies for species conservation, protected area strategies and vegetation management policy. The development of these policies roughly follows a six-stage process described in **Figure 1-1**. Despite the role of evaluation in informing all stages of the policy process, assessment of conservation policies are often missing from the scientific literature and, owing to significant resourcing constraints, do not form a compulsory component of departmental reporting.

Given increasingly limited time, resources, and imminent threats to biodiversity (Woinarski, Burbidge, and Harrison 2015b), it is imperative to evaluate protected areas and vegetation management for their contribution to the persistence of biodiversity. This thesis directly addresses this need while advancing the conservation evaluation literature. Biodiversity conservation involves the establishment, management and restoration of functional habitats and habitat networks. There are two notable mechanisms which facilitate the retention of native vegetation in Queensland: protected areas and vegetation management policies. To understand how well these mechanisms are performing, this transdisciplinary thesis combines spatial and statistical analysis with qualitative methods to describe and understand the state of Queensland's forests concerning the policies which support their retention.

1.6 A brief history of Queensland's protected areas

Timber harvesting in Queensland commenced in 1775. In response to the rapid loss of forest and subsequent riparian bank erosion, the Governor King issued a proclamation forbidding collection in watercourses (Bolton 1992). In 1823, the successful recommendation for a penal colony settlement in Brisbane resulted in a significantly increased timber harvesting (Powell 1998), and eight years later, the penal colony became a free settlement. Large tracts of native timber were felled to make way for development, local use, or for domestic consumption and export. In less than fifty years, uncontrolled timber harvesters had moved 1,600 km north, acquiring cabinet wood resources from the Atherton Tablelands (Carron 1985). Alarmed by the rate of unchecked forest clearing, the first notion of forest reservation in Queensland was described at a public meeting in May 1873. In this context, forest conservation should meet the two objectives of '*preserv[ing] and promot[ing] the growth of timber trees to conserve forests for useful purposes* (Carron 1985).' That is, the management timber dominated areas are necessary to balance appropriate future timber resources while also maximising profits and accommodating for an increasing population's demand on land resources. The crux of this concept is captured below in a statement by the Under Secretary of the Department of Lands:

"*It is an unfortunate circumstance, from the standpoint of forestry, that the State's best softwoods are found on its best soils. The maintenance of the rich volcanic coastal scrubs as permanent reservations for forestry purposes cannot be regarded as a subject for serious consideration. The demand for such land for close settlement becomes more and* *more pressing and each year sees additional areas of such land as the timber becomes cut out, excised from the reservations and opened for settlement*. (Director of Forests. 1914)"

Over time, the purposes of protected areas and reserves became more diverse (**Figure1-4**). A full historical review of this legislation supporting this diversity is provided in Appendix 1. In 1975, National Parks and Wildlife Act 1975 (1 Eliz No 20) was passed which combined the regulation of fauna conservation (previously managed by the Department of Primary Industries) and national parks into the National Parks and Wildlife Service (Queensland State Archives Agency 2016) (**Figure 1-4**). In support of this new Act, a new division of Government was created called Queensland Parks and Wildlife Service (QPWS). Then, in 1992, a new Act was created: the Nature Conservation Act (NCA) 1992 (No 20). In a historic first for Queensland, the NCA synthesized a diverse range of objectives for reservation as well as making nature conservation an explicit priority. Furthermore, the NCA provided the scaffolding for the dedication and management of protected areas.

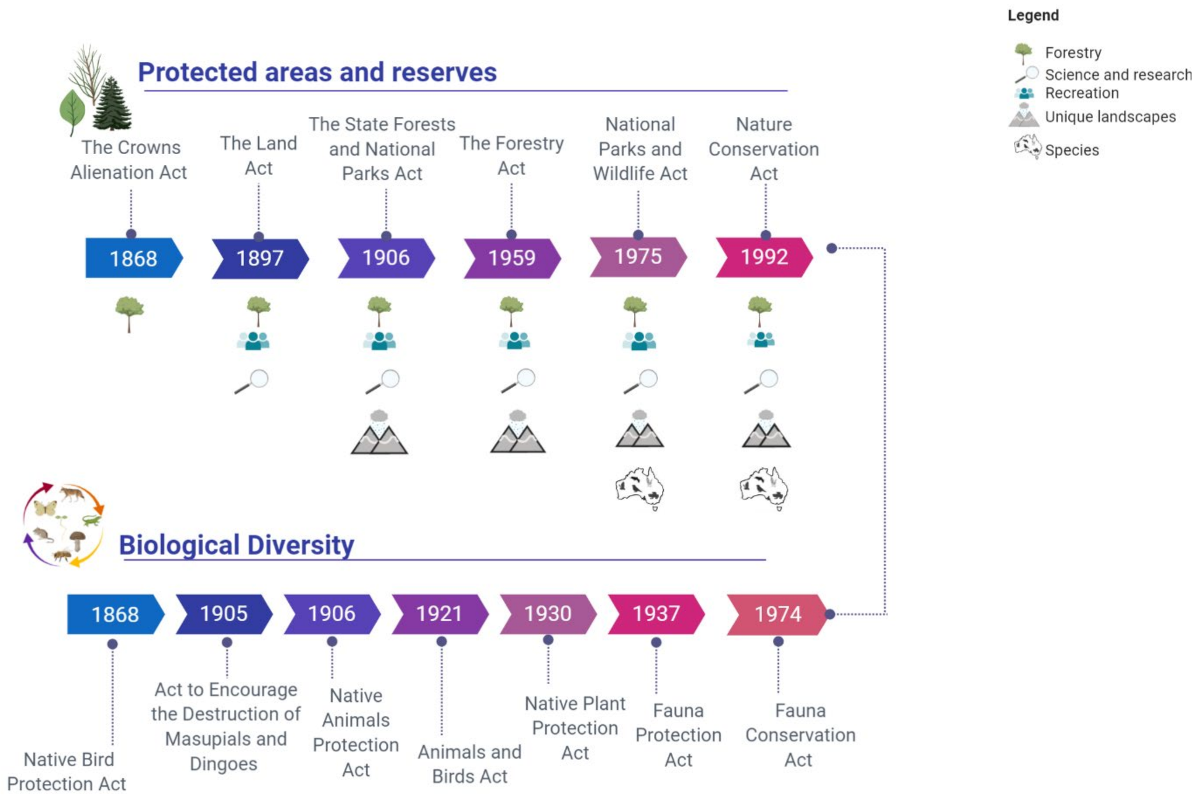


Figure 1-4: Timeline of the key protected area and biological conservation legislation in Queensland. In the top row, each piece of legislation is described with landscape features that would have been identified as priorities for protection. Here, forestry refers to areas which have significant timber potential (*ie* landscapes that would have been suitable for timber harvesting) For a review of legislation relevant to the retention of biodiversity, please see Appendix 1.

1.7 Protected areas in Queensland

Protected areas are classified by management categories. Management categories indicate the level of protection defined by the NCA as prescribed by management principles (Appendix 1). These management principles correspond to the criteria described by the International Union for Conservation of Nature's (IUCN) internationally accepted criteria (Dudley 2008). Land uses that are permitted in protected areas include such activities as grazing, mining, recreational activities (*i.e.* ecotourism facilities, horse riding and hiking trails) and timber harvesting, but, again, are contingent upon the protected area classification and possible environmental authorities (or conditions of development permits) relevant to that particular park. In general, activities likely to cause significant disturbance (*i.e.* removal of habitat) are not permitted in National Parks or areas classified with strict IUCN categories (*i.e.* categories I and II). National Parks form the largest protected area category in Queensland (7,165,307 ha, 49.9%), and there are few recreational and extractive activities permitted within the boundaries of National Parks.

Management categories capture the diverse requirements for protected areas. With the addition of new management categories over time, protected areas reflect a growing scientific understanding of the principles of reserve design, and changing social values (Cumming et al. 2015). The first reserves in Queensland were forestry caches where the initial intention behind reservation was to halt exhaustive resource extraction (Thorpe 1996, Carron 1985) while still allowing for economic growth and colonial settlement, and importantly, future extraction. Over time, other priorities have been added, including securing habitat for rare, endemic or endangered species, recreation and generating tourism revenue to bolster national economies, contribute to scientific discovery, and supporting forest caches (Dudley and Stolton 2010). Nearly fifty years later, the role expanded to preserve unique and iconic landscapes. Then, 100 years later, the protected areas became intentional investments in the permanent preservation of biological diversity (Mackey et al. 2008).

In response to policy directives to expand the protected area estate, and, as a response to the diversification of protected area roles, modern legislation has facilitated the growth of the protected area network by creating tenures which reflect the different expectation or demands on the land (Dudley and Stolton 2010). For example, in 1977, the size of Queensland's protected areas estate doubled (Pressey et al., in prep) when significant areas of the Cape York bioregion and other savannah lands were included into the network (Sattler 2014) and has continued to grow over the following decades. As of January 2020, 1,043 areas comprising 8.22% (13,068,320 hectares) of Queensland is protected or reserved for conservation under State or Commonwealth laws (Department of Environment and Science. 2019), and the map in **Figure 1-5** illustrates the total extent of these conservation commitments. These expectations reflect an increasing diversity of stakeholders. They can include conservation of unique and iconic landscapes, provision of habitat for wildlife either through the retention of critical ecosystems or by the provision of climate change refugia, contribution to the livelihood of local communities and bolstering economies through tourism revenue (Watson et al. 2014b). There is a clear need to evaluate the protected area network against each of the management priorities of protected areas. A failure to do so risks boasting extent as an outcome in its own right but an ultimate failure to achieve impact (Watson et al. 2014a). Literature suggests that, globally, protected areas are failing to represent the distribution of threatened species (Venter et al. 2018) and often fail to mitigate threatening processes such as habitat loss (Rasolofoson et al. 2015b, Geldmann et al. 2013, Andam et al. 2008).

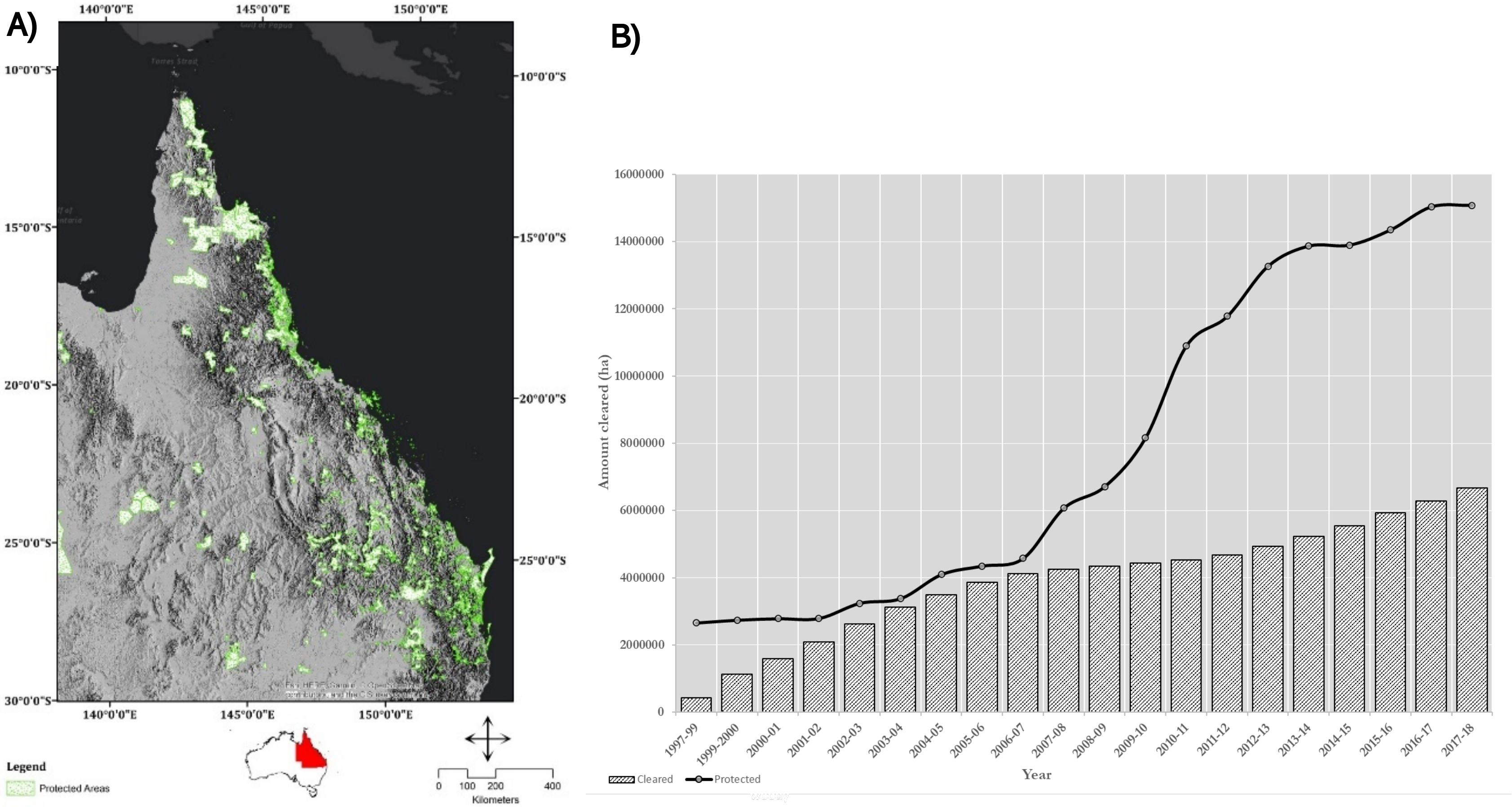


Figure 1-5: A) Current (as of January 2020) extent of protected areas in Queensland. Spatial data for protected area boundaries were sourced from the Queensland Spatial Catalogue ("Q-spatial" - (Queensland Government 2019c)). B)- Expansion of Queensland's protected areas (National Parks and Conservation Reserves) per decade. Decadal protected area growth data is available through (Pressey *in prep,* Department of Environment and Science. 2019).

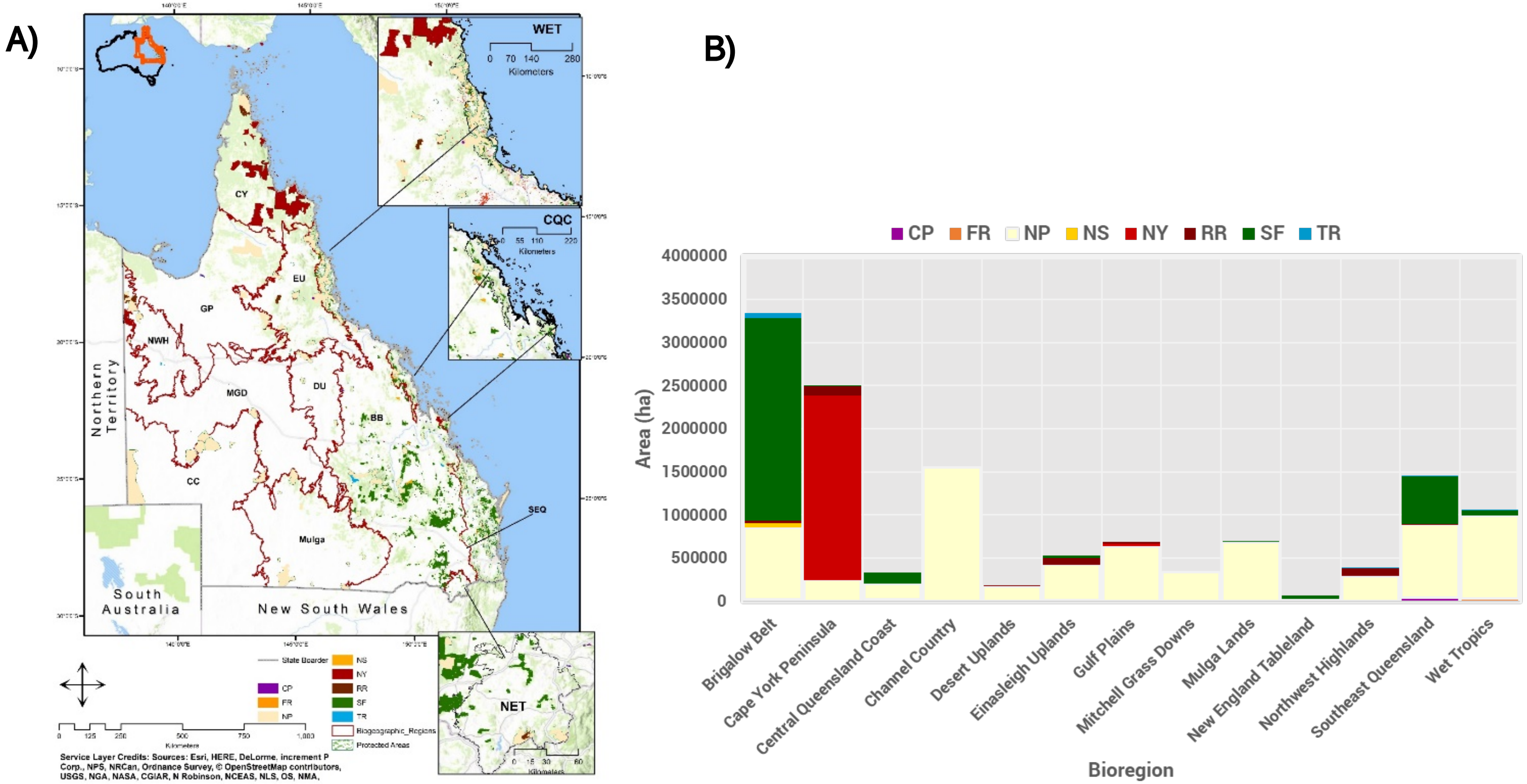


Figure 1-6: A) Map showing the distribution of conservation tenures across the State. Conservation Park (CP), Forestry Reserves (FR), National Park - Scientific, National Park (NP), National Park - Cape York Peninsula Aboriginal Land) (NY), Resource Reserve (RR), State Forest (SF) and Timber Reserves (TR). B) barplot of showing the quantity in terms of the area of each conservation tenure per bioregion. Map showing the distribution of conservation tenures across the State. Conservation Park (CP), Forestry Reserves (FR), National Park Scientific, National Park (NP), National Park Peninsula Aboriginal Land) (NY), Resource Reserve (RR), State Forest (SF) and Timber Reserves (TR). B) barplot of showing the quantity in term s of area of each conservation tenure per bioregion.

1.8 Vegetation management – the Queensland context

In the Queensland context, protected areas are not the only mechanism responsible for retaining habitat. It is equally important to understand how regulation which relates to vegetation management contributes to *de facto* protection. An area is considered to be *de facto* protected if policy interventions prevent or significantly limit clearing. In the context of Queensland's policies, vegetation which contains spatial features controlled by public policies under the Vegetation Management Act, 1999 is termed "assessable." Queensland's vegetation management policies provide an opportunity for investigating the cumulative spatial implications of a policy change.

The quality of assessment varies widely, and this may because assessments lack standardised approaches which accurately reflect the status of all biodiversity features assessed. The effective preservation of forested habitats requires sophisticated policy approaches, and the best strategies are those that facilitate effective collaboration across relevant stakeholders and all levels of Government. One method of increasing the sophistication of policy approaches is to subject assessments to independent peer review (Sheaves et al. 2016). The outcome of peer review is the greater assurance that assessments are held to the same standard required of other scientific studies. Such an advancement would be meaningful and welcome development in standards and would provide the transparency and accountability sorely lacking from the current process.

Furthermore, assessments should include a cumulative impact assessment. Cumulative impact assessments regard the features potentially affected by the proposed development in the context of all threatening processes to the feature across its distribution. Despite the first calls for cumulative impact assessments over 30 years ago, they remain rare in the environmental context (Burris and Canter 1997). A failure to systematically address cumulative impacts on environmental assets can result in avoidable and significant damage to biodiversity or ecological values. In the absence of firm and comprehensive assessments, forested habitats, and the biodiversity which relies on them will continue to decline.

1.9 Thesis rationale

Globally, the majority of terrestrial species are found in forests (Food and Agriculture Organisation of the United Nations 2016); however, increasing land appropriation for economic development has caused substantial loss of forested habitats. Forest habitat diminution is known to influence terrestrial ecosystems negatively and continues to be a leading cause in biodiversity decline and climate change. Australia is a global land clearing hotspot (Evans 2016) and its second-largest State, Queensland, has the highest rates of land clearing in the country (Bradshaw 2012, DSITI 2017a). To combat deforestation, establishing protected areas are a primary tool and are fundamental parts of international (UNEP 2011) and national (TFMPA 1999a) conservation strategies. The establishment of protected area networks is a globally utilised tool for maintaining species populations and ecosystem functions. In isolation, formally dedicated protected areas are insufficient to maintain biodiversity. However, they remain the cornerstone of conservation initiatives. Understanding their performance, as well as other habitat retention mechanisms, are essential contributions to scientific literature.

Evaluation methods have had a notably high variation (Newcomer, Hatry, and Wholey 2015, Posavac 2015, Joppa and Pfaff 2010a). In the context of protected areas, conventional evaluation methods compare species assemblages (Greve et al. 2011) and deforestation impacts relative to land adjacent (Bruner et al. 2001, Nagendra 2008) or across the entire landscape (Sánchez-Azofeifa et al. 1999). Other evaluation options include analysis of site-specific temporal variation (Gaveau, Wandono, and Setiabudi 2007). Numerous studies, however, have demonstrated, that protection tends towards environments that are considered not suitable for human development (Joppa and Pfaff 2009). Thus the use of these evaluation methods may overestimate the impact of protected areas (Andam et al. 2008, Pfaff et al. 2009). There is, therefore, a need to provide empirical evidence that protected areas are slowing or halting deforestation. I do this by conducting a rigorous counterfactual impact evaluation (Ferraro 2009, Ferraro and Pressey 2015, Pressey, Visconti, and Ferraro 2015, Nolte et al. 2013). The academic literature is increasingly calling for (Margoluis et al. 2009, Baylis et al. 2016, Ferraro and Pattanayak 2006) and utilising (Maron, Bull, et al. 2015, Gill et al. 2017, Ahmadia et al. 2015, Barnes et al. 2016) rigorous counterfactual impact evaluations conservation strategies, including protected areas (Jones and Lewis 2015) and vegetation management (Simmons, Wilson, et al. 2018).

An emerging and rigorous field of scientific analysis is impact evaluation (Ferraro 2009, Ferraro and Pattanayak 2006, Pressey, Visconti, and Ferraro 2015). Impact evaluation assesses if an intervention or strategy is achieving its targeted objectives, goals, or benefits. Applying theories of impact evaluation to conservation science provides insight into the effectiveness of conservation policy, planning, and management (Ferraro and Pressey 2015). While most scientific studies focus on measuring conditions or characteristics of conservation intervention (e.g., area, representation of ecosystems, budgets) impact evaluation measures 'avoided loss'. Avoided loss is the difference between what was achieved with the implemented conservation strategy relative to alternative arrangements, including taking no action. Importantly, robust impact evaluations assess if the habitats or species included in the protected area network are those that most critically required protection, either by the likelihood of incurring impacts by threatening processes or other factors that increase the possibility of extinction. This thesis addresses fundamental research gaps in the policies surrounding forested habitats in an area of global significance.

The outcome of this thesis is to assess current forests retention mechanisms and provide robust recommendations for policy. I do this by addressing several knowledge gaps (**Table 1-1**). I have worked closely with relevant stakeholders in designing and implementing this study so that the information herein can be usefully applied in the iteration stage of the policy process.

Table 1-1: Chapter number title and broad research question.

	Chapter Short Title	*Research Questions*
1	Introduction	What is policy evaluation? What are the research gaps in Queensland relating to vegetation community retention?
2	Drivers of protected areas establishment.	How have the strategic guiding principles in policy shaped priorities for protected areas?
3	Effectiveness of protected areas in reducing deforestation	How much of a difference to deforestation have protected areas made?
4	The implications of rapid policy changes on native remnant vegetation.	What are the implications for differences in vegetation clearing guidelines concerning the sensitive spatial features they regulate? Does this allow for more or less vegetation to be cleared without the scrutiny of a government assessment?
5	Identifying priority forested areas in Queensland	Which regional ecosystems in Queensland are most at risk of changing vegetation management status because of their high-probability of being cleared?
6	General discussion	What now? Recommendations, limitations of this study and future work.

1.10 Thesis structure

As discussed above, systematic conservation planning theories formed the conceptual underpinnings of Australia's National Reserve System. Systematic conservation planning is a globally utilised method for combating the residual nature of protected area establishment and is comprised of a non-linear 11-step framework (Pressey and Bottrill 2009, Margules and Pressey 2000a). In this framework, some processes may feedback to multiple other steps of the framework. Two steps, four and seven, of this process are fundamentally constrained by the quality of policy and decision-makers capacity to make informed and unbiased decisions. This thesis builds on the 11-step framework by refining steps four and seven within the multi-disciplinary context of impact evaluation (Baylis et al. 2015, Ferraro 2009, Gertler et al. 2016, Khandker, B. Koolwal, and Samad 2009, Margoluis et al. 2009) to inform policy design. In this thesis, I focus on policies directly related to biodiversity conservation.

1. Scoping and costing the planning process
2. Identifying and involving stakeholders
3. Describing the context for conservation areas
4. **Identifying conservation goals**
5. Collecting data on socio-economic variables and threats
6. Collecting data on biodiversity and other natural features
7. **Setting conservation objectives**
8. Reviewing the current achievement of objectives

9. Selecting additional conservation areas
10. Applying conservation actions to selected areas
11. Maintaining and monitoring conservation areas

In this chapter, I outlined the importance of Queensland as a case study for habitat retention policies and provided an overview of the environmental legal framework. I then introduce policy evaluation and its role in informing all stages of the policy process.

In Chapter 2, I explore the thematic priorities in Australian policies finding that the representation of species is the most common priority. I also find that avoided loss (or dedicated protected areas in locations which quantifiably reduces their risk of being lost) is an uncommon theme. Avoiding loss, however, is key method for demonstrating the effectiveness of protected areas considering increasing anthropogenic threats. In Chapter 3, I evaluate the effectiveness of protected areas in avoiding the threat of deforestation finding that protected areas are, in general, ineffective. In Chapter 4, I assess the policies around assessable vegetation in Queensland. I found that the frequent changes in policies have had substantial impacts on the distribution of assessable vegetation. Most recently, however, vegetation management was subjected to rigorous scientific review resulting in the decreased extent of non-assessable vegetation – or vegetation which could be cleared without requiring departmental review. Finally, in Chapter 5, I combined Queensland's vegetation mapping with deforestation probability mapping to estimate the extent to which unique vegetation communities are subject to potential clearing. I found that over half of Queensland's vegetation have biophysical characteristics which indicate a high likelihood of future clearing. In this chapter, I also demonstrate how policy definitions can be applied to threat mapping by quantifying the number of vegetation communities likely to move into a higher vulnerability category (*ie* have a higher likelihood of becoming extinct) (**Figure 1-7**). I conclude this thesis by providing an overview of each lesson learned throughout and some policy recommendations to promote the future security of Queensland's native vegetation.

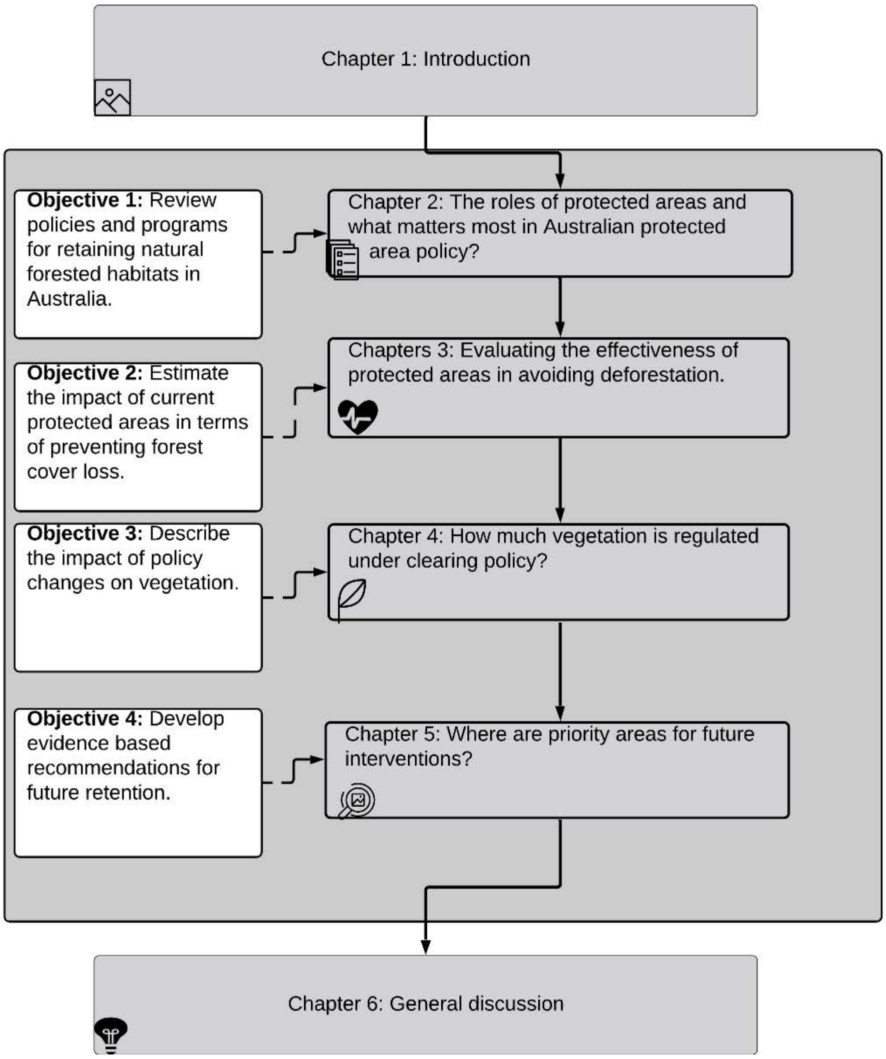
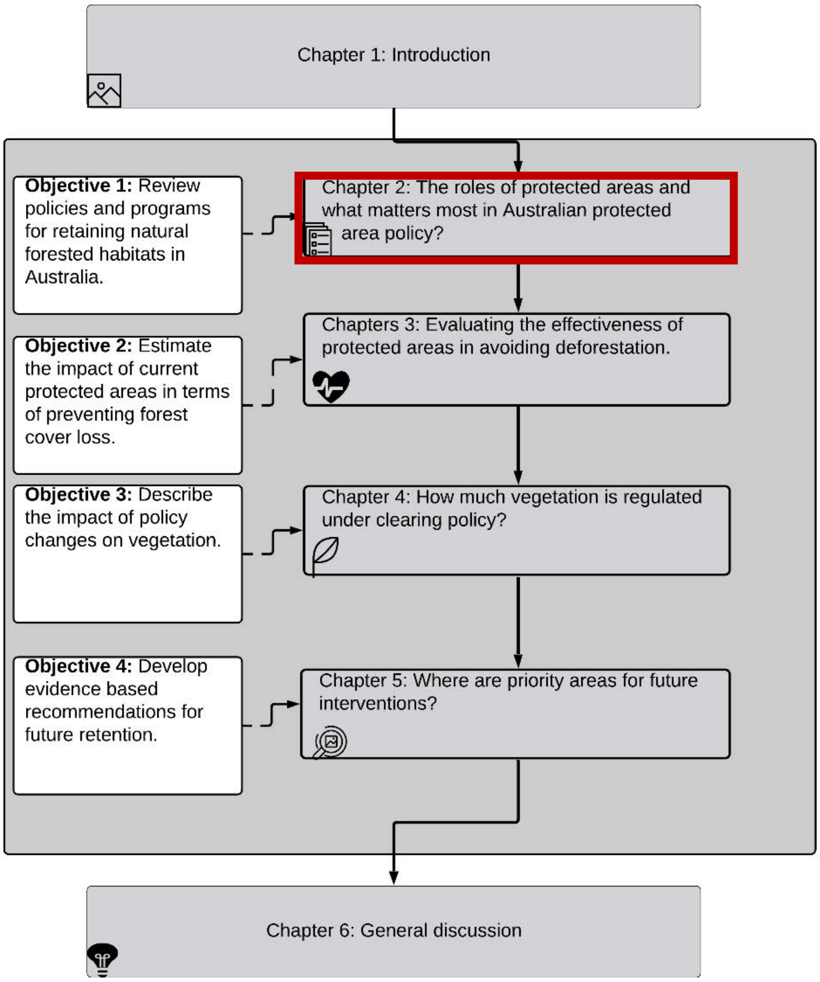


Figure 1-7: Relationship between the six chapters in this thesis, the research question they address and the methods used therein. Chapters 1 and 6 are shown in grey and do not involve analytical approaches apart from a comprehensive literature review. Chapter 2 is shown in black and uses a latent document analysis approach. Chapter 3 is shown in black and uses a doubly, robust statistical matching approach. Chapter 4 uses a simple geographic information system analysis to produce maps. Chapter 5 builds on the analysis completed in Chapter 3 to produce probability maps of areas with a probability of being cleared.

Chapter 2. What drives protected area establishment? Themes and trends from the last 27 years of Australian protected area policies[1]



[1] This chapter is based upon a paper currently in review in *Conservation Biology*

Abstract

Protected areas are a fundamental mechanism for ensuring the persistence of biodiversity. The strategic policy objectives set by governments for protected area land acquisition are strong determinants of biodiversity outcomes. An examination of these objectives is necessary to determine those most influential to protected areas. To examine spatio-temporal trends in the policy objectives for protected areas, I evaluated the strategic priorities in Federal, State and Territory policy documents across Australia using thematic analysis. I classified priorities into seven themes: adequacy, Indigenous and cultural values, representation of ecosystem and species types, threatened species and their habitat, social and recreational values, unique values and avoiding threatening processes. I found the representation of ecosystem and species types was the most prevalent theme in policy documents, and the least common theme was avoiding threatening processes. I hypothesise several reasons for this trend and warn that by emphasising extent, in terms of area or representativeness, as a goal unto itself, conservation interventions, such as protected areas, may diminish effectiveness, efficiency, and impact for biodiversity outcomes. Instead, emphasising the establishment of protected areas in locations where there are high-levels of threat would enhance the effectiveness of the protected area network. To maximise limited resources, I recommend governments commit to robust evaluations in terms of their capacity to satisfy each of the appraisal criteria identified here and a re-direction of acquisition resources to target identified gaps.

2.1 Introduction

There has been a steady global rise in both the number and total extent of protected areas, prompted by the adoption of the Convention on Biological Diversity (CBD) (Boyle 1994). This legally binding international conservation treaty focuses on promoting biological diversity through sustainable development. With 196 parties to the convention, the CBD was one of the most highly supported international environmental agreements (Secretariat for the Convention on Biological Diversity 2016) and therefore, became a crucial catalyst in the international commitment to increase the total area of land set aside for protection in signatory countries. However, despite the rapid growth of the global protected area estate, many species and ecosystems are declining towards extinction (Environment and Communications References Committee 2013), and, therefore, may not be sufficiently safeguarded in protected areas.

Numerous factors including environmental extremes, habitat loss and the introduction of feral species drive local species loss (McKenzie et al. 2007, Woinarski, Burbidge, and Harrison 2015b), with significant negative impacts on ecosystems (Hooper et al. 2012). Australia is responsible for 28% of worldwide mammal extinctions since 1600 AD, exceeding the rate of non-marine mammal extinctions of every other country (Baillie and Groombridge 1996). Recent work suggests that the decline of Australian fauna is on-going, with more than 27% of Australian species currently threatened with extinction (IUCN 2020). For example, a recent study suggested that 1 million birds are killed by feral cats every day (Woinarski et al. 2017), with unknown consequences to the population viability for Australian native birds.

In the context of increasing human pressure on the Australian environment, policy responses have been developed to prevent biodiversity loss (Kristensen 2004). Policy responses include the establishment of a series of priority-setting principles and targets. These can be value-laden and subject to fluctuating government incentives, public concern or increasing scientific knowledge. For example, a previous study found that the term 'biodiversity' has become less prevalent in environmental policy media releases while the term 'ecosystems services' has become more frequent (Kusmanoff et al. 2017). Shifts in policy priorities have known effects on biodiversity conservation (Reside et al. 2017, Barton et al. 2015) but can also result in changes to the resourcing of a policy instrument or program. An assessment of the broad changes in policy priorities is a useful source of knowledge for policymakers who need to consider future options and policy needs. Thus, there is a clear need to understand how policy instruments promoting the conservation of biodiversity can be developed to maximise the benefits for biodiversity within an evidence-based framework (Coffey and Wescott 2010). Because priorities reflect the values for which protected areas are or will be acquired, it is critical to understand how these values are represented across time and space, and, if necessary, to redirect future policy at the appropriate level to address potential gaps.

Australia committed to protecting a portion of all native ecosystems through the expansion of a protected area network (ANZECC 1996) (**Figure 2-1**). In 1992, when decision-making regarding forestry estate management underwent a full refurbishment, Australia further committed to the establishment of a robust system of protected areas and a reduction in the acrimonious conflict between production-oriented forestry and environmental or social demands on state-owned native forests (Slee 2001). This refurbishment included the release of two decisive Federal policies: the *National Forest Policy Statement* (NFPS) (Commonwealth of Australia 1992) and the *Intergovernmental Agreement on Environment* (IGAE). To ensure consistency in prioritising areas for protection across multiple regions, principles for guiding prioritisation were developed cooperatively by the Federal and State governments and the resulting agreement was known as the JANIS agreement (Janis 1997). The JANIS agreement is a framework for reserve design based on prioritisation from systematic conservation planning (Commonwealth of Australia 1992). The core principles of this framework were: comprehensiveness, adequacy, and representativeness (CAR). Comprehensiveness refers to the full inclusion of communities (such as forest community types). Adequacy refers to the integrity of an area to maintain the biodiversity in perpetuity, including its vulnerability to loss because of land-use conversion or other proximal external pressures. Representative refers to the full inclusion of fine-scale ecological variabilities of the region (such as genetic diversity, age class structure) within protected area networks (TFMPA 1999b, a, Commonwealth of Australia 1997b, Thackway and Cresswell 1995a) (**Table 2-1**). CAR principles were fundamental components of Australia's 1996 Biodiversity Strategy (Commonwealth Of Australia 1996) and became the standard evaluation and appraisal priorities declared by Federal, States and Territory Governments for the strategic protection of landscapes in association with the commitment to expand reserve networks.

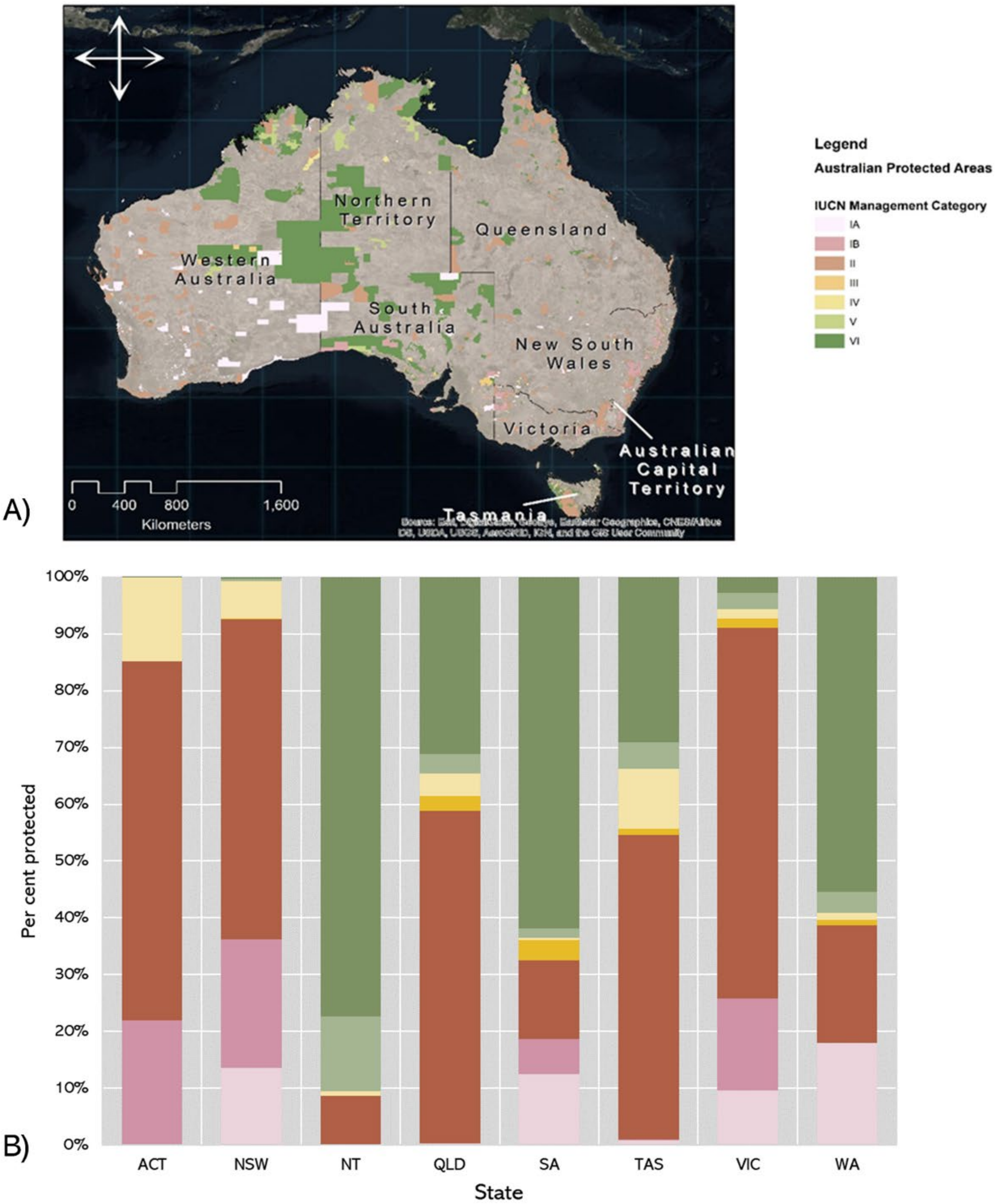


Figure 2-1: A) The spatial extent of protected areas across Australia per IUCN status and B) the per cent of each IUCN class in protected areas per State. IUCN status refers to a type of management classification. In general, areas with a higher IUCN status (*ie* I and II) tend to have fewer activities permitted (see Appendix I).

Table 2-1: Definitions of CAR (ANZECC and MCFFA 1997) and guidelines to consider for identifying comprehensiveness, adequacy and representativeness of protected areas with examples from forest ecosystems (Commonwealth of Australia 1999).

	Comprehensiveness	Adequacy	Representativeness
Defintion[a]	"*The inclusion of the full range of forest communities recognised by an agreed national scientific classification at an appropriate hierarchical level.*"	*"The maintenance of ecological viability and integrity of populations, species and communities."*	*"Those sample areas of the forest that are selected for inclusion in reserves should reasonably reflect the biotic diversity of the communities."*
Selection criteria[b]	**Does the area:** • increase the comprehensiveness of the [National Reserve System] at a continental scale, and to what extent? • add to the reservation of the full range of ecosystems recognised at an appropriate scale? And, within each IBRA^ region, to what extent?	**Does the area:** • provide long-term security for one or more ecosystems and associated species? • increase the security provided by the protected area system for one or more ecosystems and associated species, and to what degree?	**Does the area:** • add to the representativeness of the [National Reserve System] and to what degree? • enable better representation of ecosystems across their geographical or environmental range within the IBRA^ region? •include the intrinsic variability of the ecosystems it represents?

^Interim Biogeographic Regionalisation for Australia (Thackway and Cresswell 1995b)

The criteria used for park selection can precipitate naturally from the transmission of social values (Hellström and Rytilä 1998). Thus, while CAR principles are a fundamental component of protected areas strategy for Australia, they are not the only principles that guide the prioritisation of candidate protected areas. Other values associated with protected areas may include recreational or social values (*i.e.* areas for public use), iconic landscapes, or places of significant cultural or ecological value. The spectrum of values associated with the reserve estate is ultimately encased in reserve management categories (Dudley et al. 2010). These categories are a product of statutory commitments stated in legislation and reflect social values. Understanding what these values are in the Australian context and their prevalence in protected area policies and strategies over time reveals the underpinnings of current practices for reserve design. Attention to fluctuations in these pluralistic criteria is necessary for the design of future policies.

The concept of protected areas has evolved from a long-standing discourse involving geographers, forestry scientists, governments and non-government organisations (Dudley 2008). The multifaceted concept of protected areas can now involve competing objectives and priorities. To maximise limited opportunities and resources to secure biodiversity assets on finite land, it is critical to identify and describe prioritisation and policy targets, describe temporal shifts and identify any gaps in strategic reserve planning (Di Marco et al. 2016). In this article, we address two fundamental research gaps: i) which concepts and social values are commonly represented in protected area policy? and ii) how do these concepts and values vary across time and jurisdiction? This allows us to assess and identify gaps in the current framework and evaluate the link between values and conservation policy.

2.2 Methods

Australia is a federation comprising six states and two territories. I collected government documents relating to strategic terrestrial protected area planning and biodiversity strategies at Federal, State and Territory levels, coded priorities into themes, and then analysed themes for trends across time and jurisdiction.

2.2.1 *Document collection*

I collected Australian Federal, State, and Territory policies for biodiversity and protected areas for the 27 years between 1992-2019. We began our sampling in 1993 as this corresponded with the development of Australia's regional forest agreements from which the concepts of reserve design begun to appear in policy documents (Lane 1999). I searched government websites and online databases, contacted environmental departments at the State and Federal level, and searched within policy documents for references to other documents. The search terms used in the database searches were: "biodiversity" OR "reserves" OR “protected areas” OR “conservation” AND "Australia" OR “Australian Capital Territory” OR “ACT” OR "Northern Territory” OR “NT” OR “New South Wales” OR “NSW” OR “Queensland” OR “Qld” OR “Tasmania” OR “Tas” OR “South Australia” OR “SA” OR “Western Australia” OR “WA” OR “Victoria” OR “Vic.” I excluded policy documents if they did not relate to or provide directions for terrestrial protected area strategy. I also exclude reporting materials that described jurisdictional progress towards targets because these are not priority-setting strategies, though I recognise their importance in informing terrestrial protected area strategies (Miller et al. 2018).

2.2.2 Thematic analysis

Thematic analysis is useful in identifying patterns in the underlying concepts and ideas of qualitative data. To understand priorities and their prevalence (Bowen 2009), I performed latent thematic analysis on each strategic priority in each policy document using NVivo (Bazeley and Jackson 2013, Maguire and Delahunt 2017, Guest, MacQueen, and Namey 2011). I collated all priorities, objectives and actions (hereafter: priorities) described in each policy document into a datasheet. I then coded each priority into themes forming new themes until concept saturation. Concept saturation is achieved when enough information has been obtained to represent the data accurately or when new information or concepts are no longer observed (Guest, Bunce, and Johnson 2006, O’reilly and Parker 2013, Ness 2015). My coding method allowed priorities to fall into multiple themes. For example, where themes loosely corresponded to the aspects of CAR principles (*i.e.* genetic diversity is a feature of representativeness), I list these aspects as sub-nodes within the significant theme. For example, “*Adequacy”* can refer to the connectivity of the reserve estate or the capacity of the reserve estate to be a refugium for species under climate change. “*Connectivity*” and “*Refugia/Resilience*” were coded as sub-nodes to “*Adequacy.*” Notably, comprehensiveness and representation are used interchangeably, so I combine these into a single “representativeness & comprehensiveness (*R&C*)” theme.

I quantified then analysed themes across time and jurisdiction (*i.e.* concerning state/territory). To analyse themes through time, I produced bar graphs and stacked bar graphs in RStudio (RStudio Team 2015) using the package ggplot2 (Wickham and Chang 2008). Each bar segment is thematically coloured and represents the proportion of each theme per year. To analyse themes across jurisdictions, I attributed state boundaries with the proportion of each theme observed per state or territory sampling period. I produced maps of the attributed state boundaries in

ArcMap v10.7 (ESRI 2014). Spatial data for state boundaries were obtained from the Australian Government's spatial data portal (Australian Government. 2019).

2.3 Results and Discussion

2.3.1 Overview

Evidence-based, contextual analysis is critical to effective decision-making and policy development (Pullin, Knight, and Watkinson 2009). Qualitative systematic reviews, when aimed at the decisions made by on-the-ground managers, are essential tools in conservation decision-making (Cook, Possingham, and Fuller 2013, Macura et al. 2019). Here, I systematically reviewed 43 strategic biodiversity and conservation policies in Australia for the 27-years between 1992 and 2019 (**Figure 2-2).** For a full list of policies included in this analysis, please see Appendix 2**.** Seven main themes for protected area priorities emerged as unique categories from this analysis: adequacy, avoided loss, indigenous values, representativeness and comprehensiveness, social values, threatened features and unique feature I found that the strategic priorities converged on seven main themes: adequacy, avoided loss, indigenous values, representativeness and comprehensiveness, social values, threatened features and unique feature (**Table 2-1**). In this study, I did not include strategies which are not purposed with guiding decision-making frameworks specific to protected areas. Other biodiversity strategies (such as threatened species recovery plans) may also provide recommendations or strategies for guiding protected area gazettal, and should be targeted for future research.

The number of policy documents released each year ranged from zero to eight. There were no new policies identified in the following years: 1993, 1994, 1998, 2000, 2004 and 2014. In 2013, there were eight substantive policy documents released - the highest recorded during the sampling period. This is may be due to shifts in environmental policy agendas (Dovers 2013), however, further research is needed to substantiate if other natural resource or conservation sectors were also abundantly released in this year. I observed a near biannual-annual pattern wherein in the number of policy documents would range from to two to eight and then a drop-down to one or zero in the following years. Variation in the number of policies produced each year is expected as strategic policies commonly span multiple years and may be influenced by election cycles. Most policy documents were collected from Federal jurisdiction (n=11). Western Australia had the highest number of policies observed across the States and Territories (n=9). New South Wales had the second highest (n=6) followed by Queensland and South Australia, each of which each had four. Notably, the Australian Capital Territory, Victoria, and Tasmania had the fewest strategic policies identified in this analysis, each of which had two. This is to be expected for the Australian Capital Territory's because its most recent strategy covers a ten-year period between 2013-2023. Furthermore, the Australian Capital Territory represents a relatively small geographical area for which over half is already reserve estate (Environment and Sustainable Development Directorate. 2013) (**Figure 2-2**). Likewise, nearly 60% of Tasmania's land area is included in the reserve estate, and, priorities in this State are likely to reflect the management of this estate rather than strategically identifying new areas (Forest Practices Authority. 2017).

The number of strategic priorities per policy document ranged from two to 30 (**Figure 2-2**). On average, I identified 12 priorities per policy document. Thirty total strategic priorities were observed in 2013. Following 2013, there was a sharp decline in both the number of policies and priorities. Most strategic priorities were collected from Federal jurisdiction (n=11). Western Australia had the highest number of strategic priorities observed across the States and Territories (n=9) while the ACT, Tasmania and Victoria had the fewest (n=2). New South Wales had the second highest (n=6) number of total strategic priorities followed by Queensland and South Australia, each of which each had four.

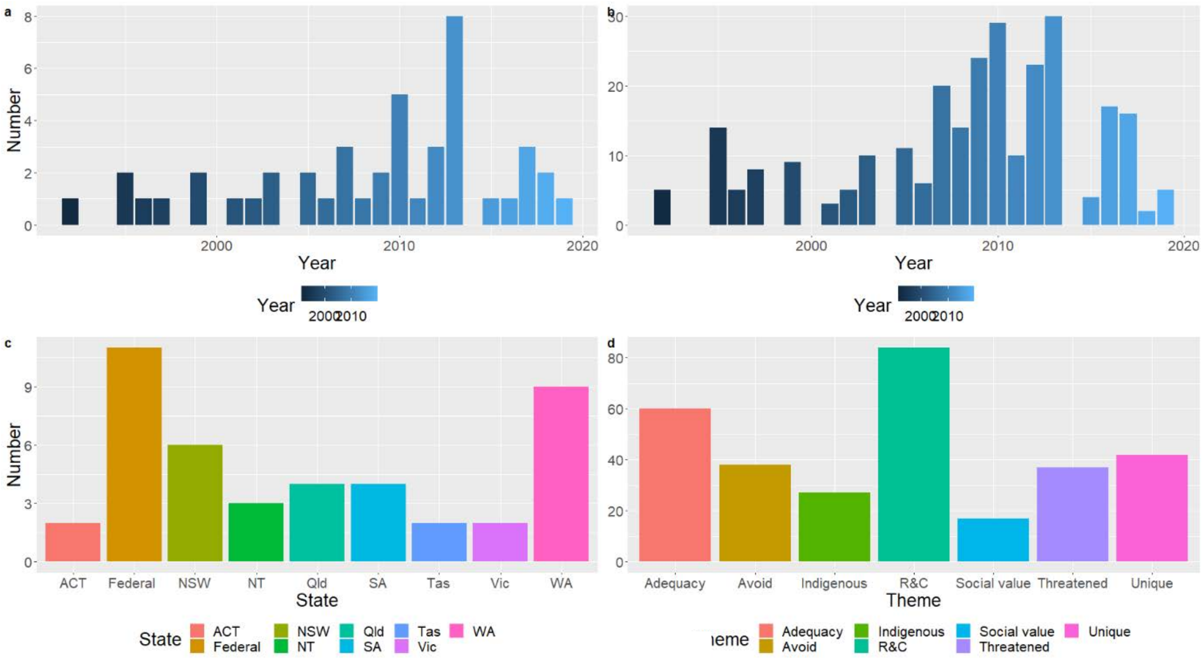


Figure 2-2: Number of policies collected for each year during the sampling period (1992-2019) (a). Number of the strategic priorities observed per year during the sampling period (1992-2019) (b), and number of policies observed per jurisdiction (c). The total number of themes identified in the sample literature (d).

Table 2-2: Major and sub-nodes identified during analysis. I define these themes and provide an example from one of the substantiative policy documents.

Major Theme	Nested theme	Definition	Example
Adequacy		Areas that are appropriately sized and configured to allow the persistence of biodiversity to perpetuity	*"Reserve design should seek to incorporate ecologically meaningful boundaries and maintain ecosystem functions and processes" (Pitman 1995)."*
	Connectivity	Prioritise areas which are contiguous with existing reserves	*"…protect perimeters of existing DECC reserves and important corridors and links between them. (DECC 2008)."*
	Refugia and resilience	Prioritise areas which are identified as climate refugia	*"By 2030, include critical areas to ensure the viability, resilience and integrity of ecosystem function in response to a changing climate, including large and small refuges (Natural Resource Management Ministerial Council. 2009)."*
Avoid		Preventing conflicting land-uses	*"The priority for reservation of a forest ecosystem is related to how much remains relative to its initial distribution and its vulnerability to threatening processes (Commonwealth of Australia 1997a)."*
Indigenous value		Having cultural value to Indigenous populations	*"…places where Aboriginal people and other landowners seek to protect cultural values (Government 2008)."*
Representativeness & comprehensiveness (*R&C*)		Sample of species, communities or other aspects of diversity	*"Eighty per cent of extant ecosystems in each IBRA sub-region15 represented in the formal terrestrial conservation reserve system by 2016 (Government 2006)."*
	Genetic diversity	Identify and conserve the genetic diversity of each species	*"securing for each component an adequate extent, abundance and suitable spatial configuration at a landscape scale within NSW to give confidence about its long-term viability, genetic diversity and evolutionary potential."*
Social value		Contributing to social well-being in the Australian community	*"Existing and new public protected areas will be managed to high standards of condition and function, recognising their significant contribution to conservation, climate change mitigation, tourism, health, recreation and economic outcomes for Queensland (Government. 2016)."*
Threatened		Species of communities listed in Federal or State legislation as 'of conservation concern'	*"Priority attention should be given to rare, vulnerable and endangered ecosystems and species (Commonwealth of Australia 1997a)."*
Unique		Having special characteristics or features	*"…number of outstanding or unique biological, zoological, geological, or paleontological features in protected areas (Government. 2007)."*

Representativeness and comprehensiveness (*R&C*) (n=84) was the most common of the seven strategic priority themes. *R&C* was present in strategic priorities for all years except 2018 & 2019 and occurred the most in 2009 (ANZECC 1997, Commonwealth of Australia 1997a) and 2012 (Commonwealth of Australia 1992). The second most common theme was *Adequacy (n=60),* which was present for all years except 2019. Likewise, *unique* species and communities were mentioned in all years except 2018 and 2019 with a maximum of six observations in 2010 (n=42).

There was a moderate representation of the *avoided loss* theme (n=38), and this theme was observed in all but six years. An uncommon theme was indigenous and cultural values (*Indigenous*) (n=27). The *Indigenous* theme did not appear in any strategic documents for seven of the sampled years, and, of the years it did occur, was mentioned once or twice per year. Priorities relating to *threatened* species and communities were mentioned in all years with a maximum of six observations in 2007 (n=37). *Social* values (such as recreation and ecosystem services) was the least common theme. It was absent for thirteen of the sampled years but was the most common theme identified in 2013. (**Figure 2-3**) (n=7).

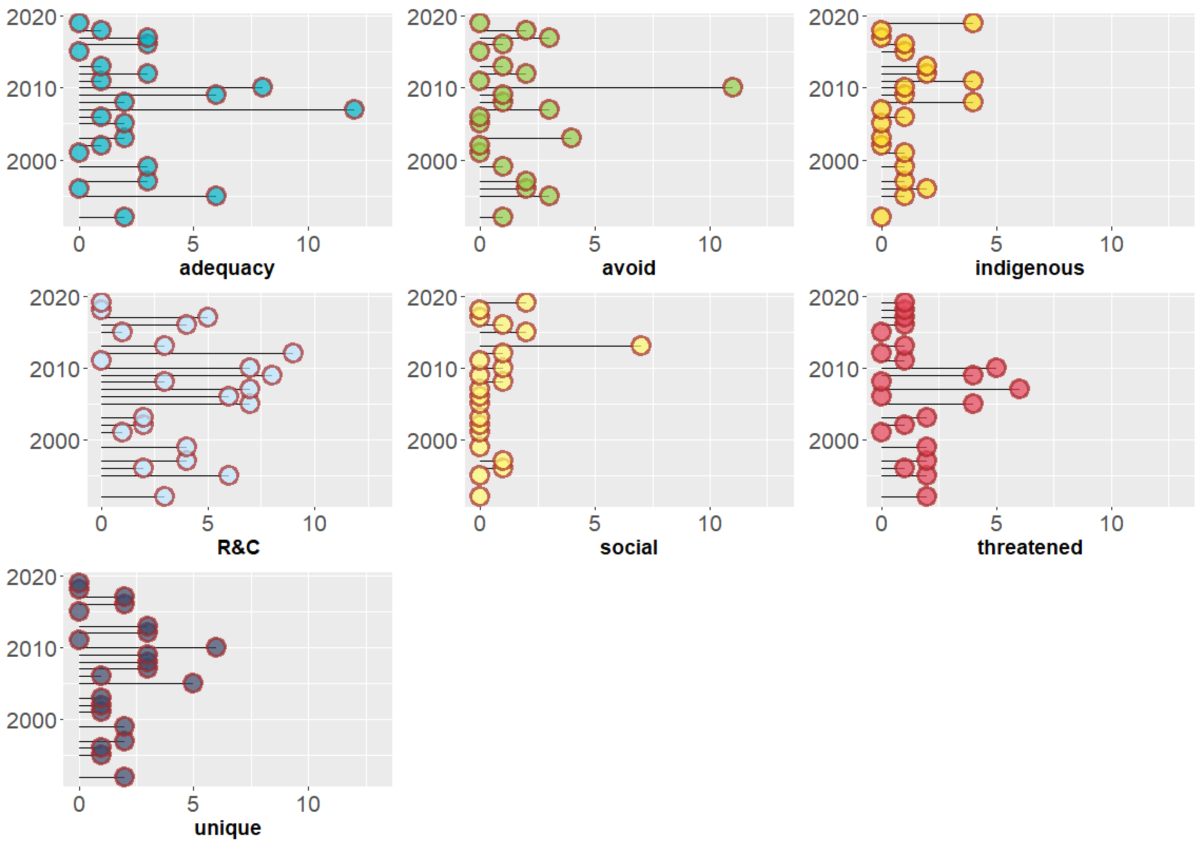


Figure 2-3: The number of times a major theme occurred in each year during the sampling period (1992-2019).

2.3.2 Jurisdictional and temporal trends

I identified and then mapped a diverse assortment of thematic priorities over time, and such diversification warrants a strategic evaluation of policy directives for conservation interventions in fulfilment of these priorities (Adams et al. 2019). While protected area planning before the 21st century, was typically devised in response to public concerns and cause célèbre (*i.e.* over-logging or declines in avian species), I found that modern policies evaluated in this study included a broader range of conservation objectives. This range of purposes consists of biological and ecological values (*i.e.* the CAR principles) and social, cultural and recreational values.

The representation of these expanded priorities, however, has not been uniform revealing a lack of policy coherence. Policy coherence is the development of policies which are mutually reinforcing to achieve national goals and objectives and is a necessary criterion for properly tackling complex socio-ecological problems (Brodhag and Talière 2006). For example*, Adequacy* occurred more frequently in New South Wales's strategic policies than elsewhere across the country (35.90%). This theme was not observed in the Northern Territory or South Australia. Likewise, half of the *Avoid* theme occurrences were from New South Wales (50%) policy documents, followed by Western Australia and Victoria (15%) (**Figure 2-4**). A possible consequence of directing Federal level resources towards a specific goal or activity is that it may fail to recognise the context specific conservation challenges and nuance within different States and Territories. Conversely, while different strategic policies between states maybe reflect their unique conservation challenges, a lack of policy coherence, such as the unequal distribution of priorities demonstrated here, risks undermining non-aligning priorities (Barry, King, and Matthews 2010, Brodhag and Talière 2006) by shifting resources towards a particular goal or activity across the nation. Thus, the adaptive capacity of Federal policies must allow for regionally specific challenges. How best to achieve this will require further research.

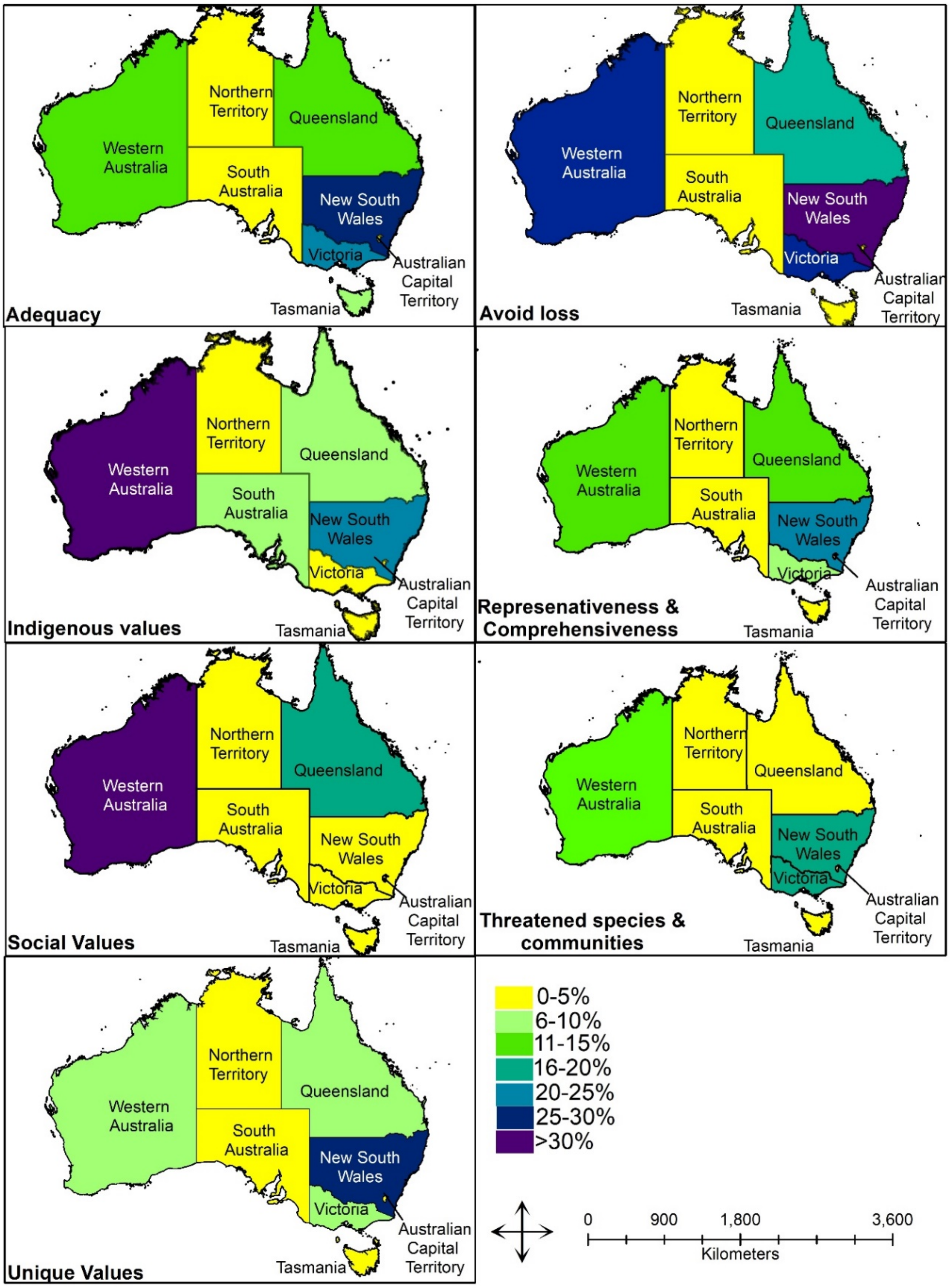


Figure 2-4: Proportion of each thematic priority per State or Territory. Each panel corresponds to a theme. Higher proportions are shown in purple and lower proportions are shown in yellow.

2.3.3 Extent-based methods and avoided loss

The theme "*Representativeness and Comprehensiveness*" appeared the most frequently in policy documents across jurisdictions and through time. *R&C* was common in New South Wales (28%), Western Australia and Queensland (24, 22%). This theme also appeared in the Northern Territory (2%) and Victoria (10%) and Tasmania (6%) but not the Australian Capital Territory, and occurred at least once in all but three years (2011, 2018, 2019). This reveals that R&C is the fundamental principle for Australian protected area policy, reflecting habitat protection goals on a global stage (Dudley et al. 2010, Secretariat for the Convention on Biological Diversity 2016, UNEP 2011). Prioritising R&C can be broadly attributed to the simplicity of application and monitoring, and also because the guiding principle (CAR) was a fundamental aspect of the initial international agreements.

Despite the prevalence of such quantifiable priorities in policy documents, area-based targets for R&C have been widely criticised as politically expedient but failing to accurately reflect scientific knowledge on biodiversity conservation requirements (Tear et al. 2005, Svancara et al. 2005, Rondinini and Chiozza 2010, Woodley et al. 2012, Barnes et al. 2018a). For example, considering Australian vegetation, the representation of vegetation communities in protected areas is, even at a coarse scale, non-representative (Appendix 1, Appendix 2). That is, the most highly represented vegetation types in protected areas are cool, temperate rainforests where over 60% of the distribution of the total extent of these vegetation categories are captured in protected areas (NVIS category 1; 65%), Eucalyptus low open woodlands with hummock grasses (NVIS category 18; 63.21%) and Eucalyptus open forests with a shrubby understory (NVIS category 4, 60.17%). The least represented vegetation communities were Eucalyptus woodlands with a tussock grass understory with less than 15% of its total distribution is capture in protected areas (NVIS category 9; 7.42%), Tropical Eucalyptus open forests and woodlands with a tall annual grassy understory (NVIS category 7; 8.96) and Tropical mixed-species forests and woodlands (NVIS category 11; 11.69%). This discrepancy might be because of the well-documented bias in protected areas towards non-productive land (Joppa and Pfaff 2009), but may also be because ecosystem mapping varies in resolution across jurisdictions. A variation in mapping resolution makes comparisons across regions challenging. For example, Queensland has mapped over 1,500 unique vegetation communities across its 13 IBRA regions at a scale of at least 1:50,000 (DSITI 2017b). In other words, 1cm on a map of regional ecosystems corresponds to 500m on the ground. At present, no other state or territory has completed a complementary set of vegetation mapping, and decisions around representativeness are limited to the resolution of the federal data. The Federal data used for planning purposes in states without detailed vegetation mapping contains, at most 99, categories of vegetation (NVIS

Technical Working Group 2017). While these are mapped at a 100m*100m resolution, the data reflect only the dominant vegetation type of the area and do not contain microhabitats or vegetation communities which may exist at a higher resolution. Limited data to support decision-making, combined with conservation targets that fail to reflect a particular biodiversity feature adequately, could result in the unanticipated decline biodiversity (Svancara et al. 2005) even as protected areas networks continue to grow (Butchart et al. 2012, Jenkins et al. 2015).

Biodiversity declines are preventable if priority, evidence-based approaches, are actioned that adequately reflect socio-ecological values (Eklund et al. 2018). A commitment to *R&C* suggests a commitment to systematic conservation planning (Margules and Pressey 2000b) principles, and to scientific principles broadly. Systematic conservation planning is a operational model for maximising the effectiveness of a reserve network while also minimising costs (Margules and Pressey 2000b). In its original design, systematic conservation planning consisted of six stages. Stage two of the process included “identifying conservation goals for the planning region” and suggested setting quantifiable conservation targets for species, vegetation types or other biodiversity features. These quantifiable targets may include the number of species per unit area. At its core, the CAR principles have adopted this planning process, but have not adopted more recent conservation planning design principles. Modern conservation planning principles clearly state that only targeting systems or species known to be at risk represents an *ad hoc* approach to reserve design (Watson et al. 2014b, Carwardine et al. 2009, Adams, Barnes, and Pressey 2019). Reporting extent as the critical measure of success falsely assigns area-reserved as an outcome of biodiversity conservation policy, rather than (more correctly) assigning area as a single input to a comprehensive decision process for effective conservation outcomes because targeting species or area does little to prevent future decline or anticipate species or communities at risk of becoming threatened (Ferraro 2009, Ferraro and Pattanayak 2006, Cook, Valkan, and McGeoch 2019). By contrast, the “*avoided loss*” theme, which requires strategic planning for current and emerging threats was far less common. This indicates that the priorities do not anticipate and or plan for threatening processes, but rather, attempting to manage them as they emerge. Other priorities (such as whether or not a protected area network adequately preserves species and ecosystems in the presence of a rapidly changing climate) require a more sophisticated approach with the consideration of a counterfactual scenario (Adams, Barnes, and Pressey 2019) and are less common in policy documents. Difficulty in evaluating objectives relating to threatened species or communities combined with a lack of quantifiable targets can hinder the prioritisation of protection in areas that may urgently require it. This can ultimately result in the continued decline of species and communities as areas under high-threat are not objectively prioritised.

2.3.4 Indigenous and social values

Land in Australia continues to play a profound cultural, economic and spiritual, role for Indigenous Australians, who have managed native landscapes for tens of thousands of years. In my analysis, I note that indigenous values were most frequently represented in policy documents from Western Australia 55%) followed by New South Wales (25%), and this trend became more frequent through time. A significant driver for this theme is the Indigenous Protected Area Program which emerged in 1997 (Australian Government. 2008). Indigenous Protected Areas are jointly managed by Indigenous Owner groups through on-going voluntary agreements with the Federal Government. My results noted that Indigenous values tended to be poorly represented in protected area strategies even in areas where there are numerous Indigenous Protected Areas (*i.e.* the Northern Territory). This may be because workshops or other consultations with Traditional Owners may occur as a separate process which is not reflected, specifically, in conservation planning documents. This highlights a potentially disparate process in terms of unifying protected area objectives. As there is increasing global recognition for cultural values (Stevens 2014), caution must be exercised when defining the cultural values for protected areas. Fitting protected area categories around cultural practices has been criticised as a simplification because it fails to adequately reflect cultural evolution in response to changing economic, political and social needs (West, Igoe, and Brockington 2006). Thus, Indigenous people across Australia must be involved in all stages of the consultation and priority setting process to ensure that cultural values are appropriately represented in both their traditional and modern understandings and use for the land (English 2000).

The *Social values* theme was extensively represented in Western Australia (64%) and Queensland (21%) and also appeared in New South Wales and South Australian (7%) and became slightly more prevalent through time. This increase is perhaps due to increasing attention given to the social, recreational values of protected areas by both governments and members of the public that has been documented by (Angulo-Valdés and Hatcher 2010, Calvet-Mir et al. 2015, Tenkanen et al. 2017). Increased attention has led to the development of programs and policies that have the purpose of promoting protected areas for their role in human health and well-being (Millennium Ecosystem Assessment 2005, Dustin et al. 2018, Victoria 2015). In Australia, this is promoted through initiatives such as the "Healthy Parks, Healthy People" where parks are beneficial because they provide opportunities for physical activity, provide sanctuary from urban stresses, and help people connect with and explore the natural world (Minnamurra 2009, Victoria

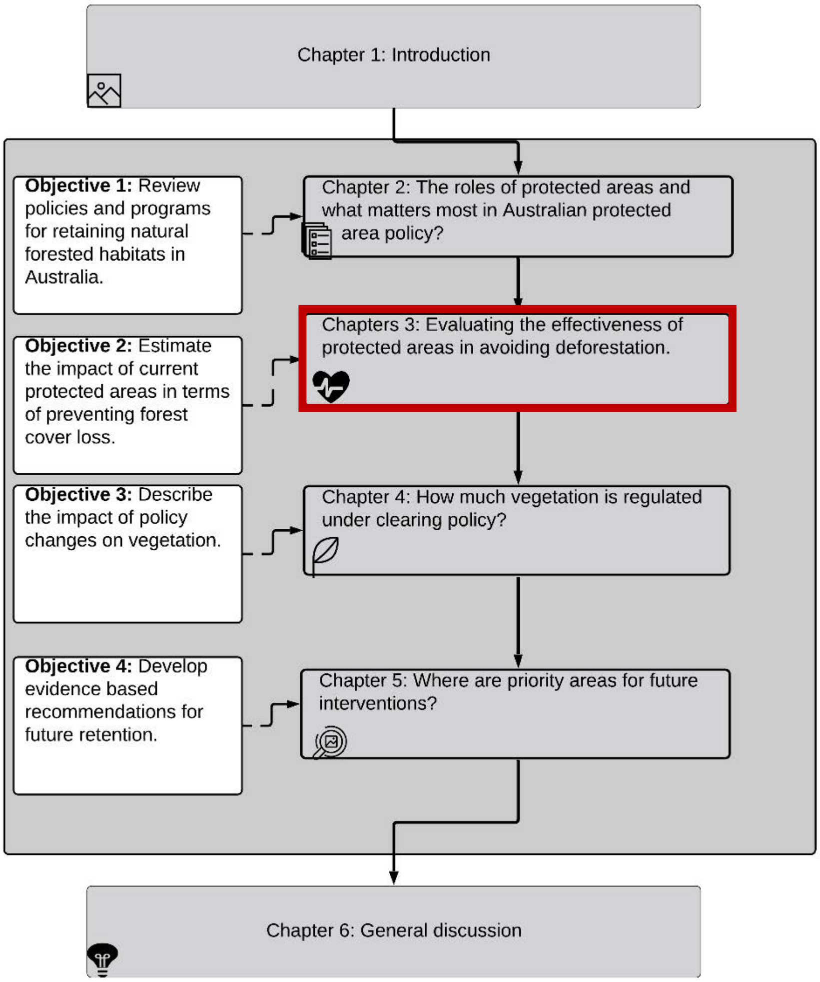
2015). Increasing human well-being is facilitated by increased tourism to local and iconic national parks; however, the effectiveness of such programs is not well-understood (Taff et al. 2019). It is understood, however, that tourism occurs in areas branded as iconic (Buckley 2004) and those which contain structures for recreation (*i.e.* picnic benches and sanitary facilities). As social values become increasingly important in Australian policy, transdisciplinary research that evaluates the impact of national parks on health and well-being is needed.

2.4 Conclusion

It has been nearly 40 years since the development of cross-jurisdictional protected area priorities in Australia (Commonwealth of Australia 1997a). Nowadays, given an increased understanding of modern threatening processes and the stark reality of climate change, it is essential to review what was meant by the original "CAR" priorities within the context of modern science and social values, and redirect future polices for better cohesion across jurisdictions.

Policies are the backbone by which conservation objectives relating to protected areas are achieved. A firm understanding of the conservation impacts associated with particular policies and strategies is, therefore, necessary to contextualize how the system currently operates and provide an understanding of the drivers of reserve selection. My systematic review of policy documents between 1992 and 2019 revealed differences in the strategic priorities for protected areas between jurisdictions and over time. It was clear that, despite sharp criticism in the scientific literature, representativeness and comprehensiveness in policy appear consistently across time and jurisdictions. Immediate outputs of this priority (*i.e.* increased areas in reserve systems) may appear satisfactory, but it is challenging to demonstrate long-term benefits in terms of beneficial outcomes for biodiversity. Other, more challenging priorities (such as avoided loss) are likely to drive the establishment of more effective protected areas but were far less prevalent in policy documents. Future policies that incorporate a cross-jurisdictional approach may help minimise the current lack of policy coherence. To maximise the future benefit to cultural, ecological and social values, it may also be beneficial to contain outcome-focused priorities which are directed at anticipating and planning interventions strategically for each thematic value identified here.

Chapter 3. Impact of protected areas in a deforestation hotspot.[2]



[2] This chapter is based on a journal article currently in review in *PLOS Biol*

Abstract

Intact forests support globally significant environmental values including carbon sequestration and storage, water cycle regulation, indigenous culture and heritage and biodiversity. Deforestation pressure threatens Australian biodiversity by exacerbating climate change and reducing the area of suitable habitat available to species. Protected areas are a key conservation strategy for avoiding deforestation and retaining biodiversity, and it is crucial to know how effective they are at achieving this purpose. Using a case study from Queensland, Australia, I identified and controlled for bias in the allocation of strictly protected areas (IUCN Class I and II) and evaluated their impact (in terms of avoiding deforestation) using statistical matching methods. Over the 30 years between 1988 and 2018, approximately 70,481 km^2 of native forest was cleared in the study region - marking Queensland a global deforestation hotspot. Using statistical matching, I estimated that 10.5% (1,447 km^2) of Category I and II (strict) protected areas would have been cleared in the absence of protection. I found that 89.5% of the protected area estate would not have been cleared even in the absence of protection, suggesting that protection made little difference to deforestation in these areas. While previous studies have used statistical matching at a country or state level, I conducted an analysis that allows regional comparison across a single State. I observed a high regional variation whereby areas that were highly protected also had lower amounts of clearing and a lower causal impact. My study demonstrates that current protected areas are largely ineffective at preventing deforestation, likely due to biases in establishment towards unproductive land.

3.1 Introduction:

Intact forests are indispensable as they support exceptional environmental and social values (Watson et al. 2018). Covering roughly one-third of Earth's landmass, forested habitats represent one of the most economically, ecologically and culturally valuable habitats to humankind (Fritz-Vietta 2016). In addition to being some of the most biologically diverse terrestrial environments (DeAngelis 2008, FAO 2010), more than 1.6 billion people rely on forests for their daily subsistence needs (Ghimire and Pimbert 1997), and they also play a crucial role in climate change mitigation. Recent estimates suggest that forests absorb one-third of annual carbon dioxide emissions released from fossil fuels and contribute to a healthy atmospheric balance of oxygen, carbon dioxide and humidity (Reich 2011).

Despite these values, forests are imperilled by human activities such as agriculture, infrastructure and urbanisation (Venter et al. 2016). Such activities, directly and indirectly, cause deforestation. To mitigate the effects of clearing, the world has committed to both the sustainable use of natural resources and the expansion of protected area networks (Brooks et al. 2015, Messerli et al. 2019, Díaz et al. 2015). Protected areas are a central instrument in the management toolkit for preventing broad-scale clearing. Global action to expand protected area networks is underpinned by the assumption that, among other objectives, protected areas will effectively abate deforestation. Testing this assumption is critical to measure the impact of protected areas, and to direct policy at multiple scales of governance. Impact is, the difference made compared to if the action was not undertaken. In this context, impact is defined here as the amount of deforestation avoided as a result of protection, relative to the counterfactual scenario of no protection (Pressey, Visconti, and Ferraro 2015). Policy directives must be well informed to ensure investment in conservation actions make a quantifiable difference to conservation outcomes and are directed to maximise impact (Ferraro and Pattanayak 2006, Adams, Barnes, and Pressey 2019, Visconti, Butchart, Brooks, Langhammer, Marnewick, Vergara, Yanosky, Crowe, et al. 2019, Barnes et al. 2018a, Pressey, Weeks, and Gurney 2017).

Protected areas are often located on land which is unsuitable for commercial or extractive activities (*i.e.* steep slopes and or having low productive capacity (Joppa and Pfaff 2009, Pressey et al. 2002, Miranda et al. 2016)). Protected areas in such locations are unlikely to be cleared in the first place, and evaluation methods which fail to account for this are likely to overestimate the impact of protection (Andam et al. 2008, Pfaff et al. 2009). Further, as protected areas tend to be long-established, researchers and practitioners are faced with the fundamental problem of causal inference: it is impossible to observe what would have happened to protected areas in the absence of protection (Holland 1986).

To ensure resources directed at conservation initiatives are used to their maximum capacity, credible information regarding the effectiveness of conservation interventions is fundamental. In Australia, the coverage in protected areas afforded to native species by protected areas has been assessed (Barnes et al. 2015, Taylor et al. 2011), as has the protected area network's capacity to manage threats (Kearney et al. 2018) and meet species or community representation targets (Barr et al. 2016). Such studies have shown that protected areas in Australia tend to underperform, but the effects of protected areas on avoiding deforestation have not yet been carefully examined. A growing body of literature is calling for robust impact evaluations (i.e. evaluations which can attribute causality between an intervention (in this case, protection) and specific observable variables (in this case, the biophysical characteristics of land and deforestation) as part of a broader movement towards evidence-based policymaking (Gertler et al. 2016). Recent literature has increased the prominence of rigorous impact evaluations (McKinnon et al. 2015), and yet they remain rare in conservation literature (Pattanayak, Wunder, and Ferraro 2010, Baylis et al. 2015, Ferraro 2009, Schleicher, Eklund, et al. 2019b). There are efforts to improve evidence standards, but they are hindered by resourcing constraints (Curzon and Kontoleon 2016), lack of technical capacity, perceived misalignment with core-business (Craigie et al. 2015), and the mistaken assumption that more straightforward approaches will yield sufficient evidence to support policy (Rose et al. 2019, Adams, Barnes, and Pressey 2019). This has resulted in limited uptake of robust impact evaluations in conservation science (Baylis et al. 2015). Consequently, conservation interventions (such as protected areas) are not adequately assessed in terms of impact, and there is a risk that scarce resources might be misplaced.

Queensland is Australia's second-largest state, and its diverse and iconic landscapes support globally significant biodiversity (Queensland Government. 2019). Queensland is home to 85% of Australia's native mammals, 72% of native birds, 50% of native frogs and reptiles and more than 11,000 plant species (Cresswell and Murphy 2017). This region of rich biodiversity is also a global deforestation hotspot, experiencing some of the world's highest deforestation rates, averaging nearly 400,000 ha per year (Hudson 2019). Despite a decline in global land-clearing over the past 35 years (Song et al. 2018b, Song et al. 2018a), land-clearing has been steadily increasing in Queensland over recent years (Queensland Department of Environment and Science 2018, Reside et al. 2017, Evans 2016). The Australian Federal Government and Queensland State Government have committed to acquiring areas under high threat of deforestation for protection (Commonwealth of Australia 1997a) by securing land from activities that conflict with nature conservation (Commonwealth of Australia. 2015). Still, the extent to which protected areas contribute to this commitment is unclear. Despite the globally significant values, a recent audit found there are no government strategies in place to systematically plan effective conservation actions (Queensland Audit Office. 2018), including protected areas.

To effectively plan future conservation actions, an audit of the current Queensland protected area network assessing its effectiveness in preventing deforestation is crucial. Here I estimate the amount of clearing avoided due to protected areas in Queensland comparing two methods: statistical matching using biophysical characteristics and a naïve comparison using logistic regression without matching. I also investigate regional differences in amount (in terms of per cent and area) of avoided clearing. The findings of this work have clear implications for the future management and conservation of Queensland's forests. Understanding impact in this context is critical to improving recommendations for new protected areas as networks continue to expand, not only in Queensland (Queensland Government. 2017) and Australia (Australian Government 2016) but also globally as a result of international obligations (UNEP 2011, United Nations 2014).

3.2 Methods:

The goal of this analysis is to measure the impact of the Queensland protected area network on deforestation. I measured impact (i.e. avoided loss) as the difference in deforestation between protected areas and statistically similar places without legislated protection (Gertler et al. 2016). I compared two types of evaluation to estimate impact; 1) using regression analysis on statistically unmatched data and 2) using regression analysis on statistically matched data. I used the estimated impact to quantify the extent to which deforestation was avoided because of protected areas.

3.2.1 Study area

The study area (Queensland, Australia) is divided into 13 bioregions. Bioregions demarcate distinct areas based on climate, geology and biota (Thackway and Cresswell 1997) and are the reporting unit for assessing the extent of protection of ecosystems in Australia's National Reserve System (Environment Australia 2000). I excluded four grassland-dominated bioregions (390,000 km^2 or 22.2% of land area in the State) because such habitats are incompatible with the deforestation outcome (described below).

Queensland's protected area network covers 8.21% (130,493 km^2) of the total land area (1.85 million km^2) in the State (**Figure 3-1**). Each protected area has an IUCN classification (Dudley and Phillips 2006) which specifies the management strategies for the area. The strictest IUCN Classes (I and II) prohibit broad-scale land clearing outright. I constrained my analysis to 'strict' protected areas (IUCN Class I and II) established in 1988 or later (Appendix 3). The total extent of IUCN

Classes I and II protected areas declared after 1988 was 49,536 km² or 38% of Queensland's current protected area network and 2.9% of the total land area.

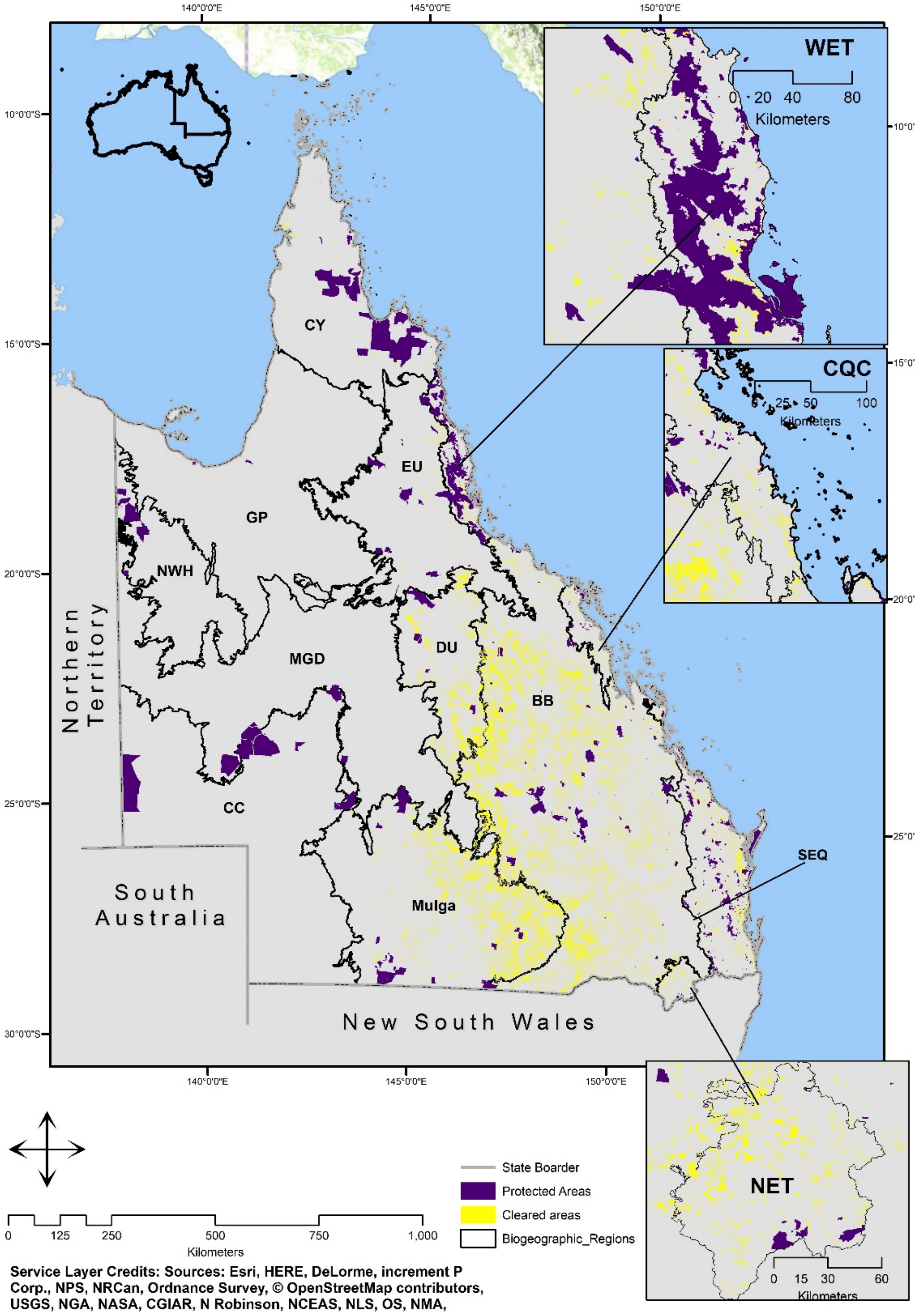


Figure 3-1: Distribution of strictly protected areas declared after 1988 and the extent of clearing which has occurred since 1988. Grey bioregions were not considered in this analysis. The studied bioregions are Brigalow Belt (BB), Cape York (CY), Central Queensland Coast (CQC), Desert Uplands (DU), Einasleigh Uplands (EU), Mulga Lands (Mulga), New England Tablelands (NET), Southeast Queensland (SEQ) and Wet Tropics (WET).

3.2.2 Deforestation

I measured the impact of protected areas as a function of avoided deforestation. Deforestation was defined as a change from forested landscapes (forests and woodlands) to a non-forested land cover. I used State Government land-clearing data (based on Landsat 7) for tree canopy cover to assess deforestation (Dadhich and Hanaoka 2010, Green, Kempka, and Lackey 1994, Koh et al. 2011). This remotely sensed deforestation data combines a spectral clearing index derived from short wave infrared bands, the density of tree foliage, and an index of variability over time to calculate a "probability of woody vegetation clearing" index (Wedderburn-Bisshop et al. 2002). Produced by the Queensland State Government under the "State-wide land and trees study" (SLATS), this data has a resolution of 30m*30m and was available from 1988-2018. (Department of Science 1988-2016). I excluded areas attributed as "natural tree death" or "natural disaster damage" from further analysis. Thus, the outcome variable was binary, with a value of "1" indicating that a pixel contained woody vegetation before 1988, but was deforested at any point between 1988 and 2018. Values of "0" indicated no change in forest cover. Areas that were deforested before 1988 were also given a value of "0," but were excluded from the impact analysis (discussed in 3.2.8).

3.2.3 Quasi-experimental design

Quasi-experimental methods construct a plausible counterfactual comparison group with similar biophysical characteristics to treatment sites (i.e. protected areas). Such methods are a robust approach for ex-poste policy evaluation, or where true experiments are not feasible (i.e. due to ethical constraints). Since it is impossible to observe what would have happened to protected areas in the absence of protection (Holland 1986), quasi-experimental evaluation methods were employed to evaluate the ex-poste impact of protected areas as a policy mechanism (Stuart and Rubin 2008, Kirk 2007, Blackman 2013, Jusys 2018). Specifically, I utilised statistical matching (hereafter referred to as matching) by pre-processing data such that the effect of protection was decoupled from the influence of co-variates that could also influence observed outcomes by producing a statistically reasonable counterfactual group (Stuart 2010). To be considered statistically reasonable, the counterfactual group had to be similar to the protected group in variables that influence either likelihood of protection or of deforestation (hereafter, co-variates). Counterfactual areas were then used as a proxy to estimate the otherwise unobservable conservation outcomes of protected areas had they not been protected. This allows us to mimic a randomised control trial within the context of an ex-post study.

3.2.4 Identification of relevant co-variates

Protected areas are expected to retain habitat and secure biodiversity in the long-term by preventing deforestation. Protection and deforestation are both predicted and influenced by biophysical and landscape characteristics. For example, deforestation for pastoral production is Australia's primary driver of deforestation (Department of Climate Change and Energy Efficiency. 2017), and in Queensland, more than 88% of the State is used for primary industry (86% for pastoral production, and 2% for broad-acre cropping) (Department of Agriculture and Fisheries 2018). Land suitability in terms of grass biomass is a predictor of both deforestation and protection because areas with high grass biomass represent prime cattle country. Woodlands with high capacity for grazing are more likely to be cleared for this purpose and are therefore unlikely to be protected. Thus, I developed a theory of change to guide the selection of co-variates (**Figure 3-2**) and identified candidate co-variates known to predict deforestation in this context. These were: distance to population centres, distance to roads, distance to watercourses, grass biomass, land zone (geological information), rainfall, slope, shaded relief, temperature and vegetation type (Laurance et al. 2002, Andam et al. 2008, Cuenca, Arriagada, and Echeverría 2016, Veldkamp and Lambin 2001a), (**Table 3-1**). All data were sourced from the Queensland Government's publicly available spatial catalogue – "QSpatial" (Queensland Government 2019c). I performed data preparation and cleaning in ArcGIS 10.2.1 (ESRI 2014). All data were rasterised into the same spatial extent and resolution (250*250 m pixel size) for analysis. A resolution of 250 m was chosen because it is sufficient to maintain mapping accuracy for use in predictive modelling (Hengl et al. 2015, Storlie et al. 2013) (Appendix 3**)**.

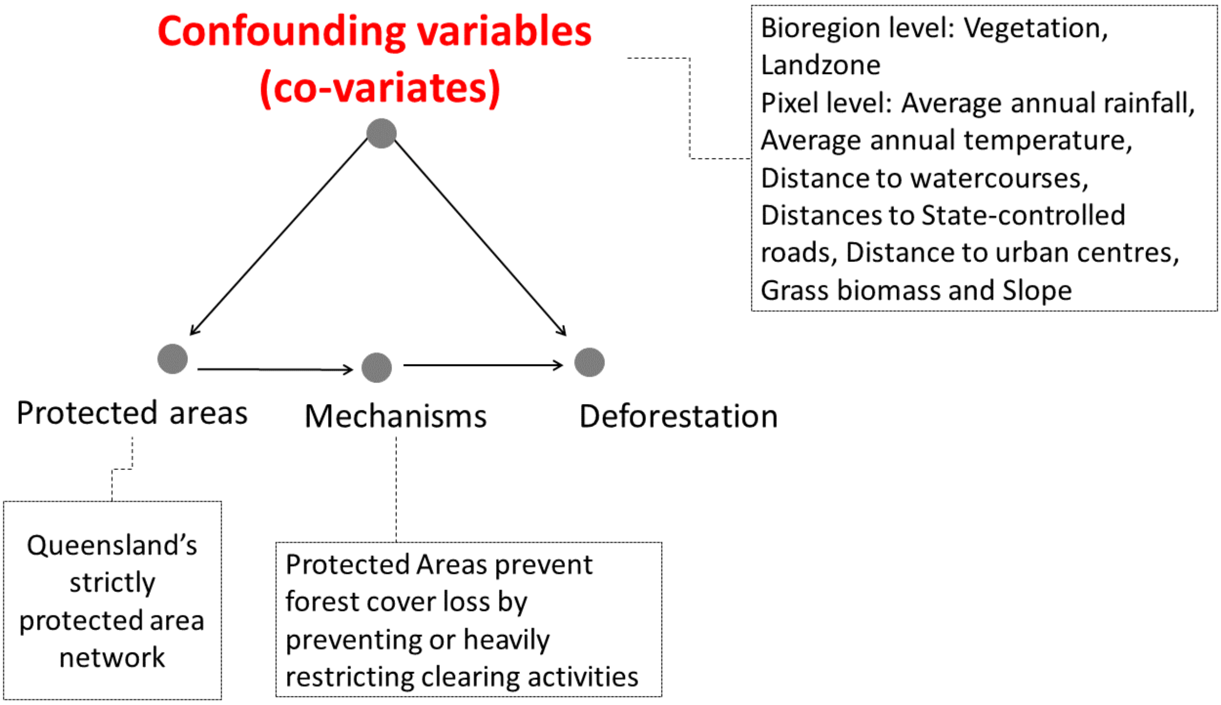


Figure 3-2: Causal pathway depicting the influence of covariates on forest cover loss and protection. The impact of protected areas is the retention of forest cover that would have been lost without protection.

Table 3-1: Description of each co-variate, including the logic behind its inclusion, the dataset name, data authority, year published, and data type. Data authority names are: Commonwealth Scientific and Industrial Research Organisation (CSIRO) Department of Environment and Science (DES) Department of Agriculture and Fisheries (DAF) Department of Natural Resources, Mines and Energy (DNRME). Restrictions in the protected and unprotected matched pairs describes how matching acts to reduce the differences in the co-variate distributions.

Co-variate	Rationale	Restrictions in protected-unprotected matched pairs	Data type
	There are higher costs associated with extracting from lands that are further from current urban areas (Chomitz and Gray 1999).	Minimise the mean standardised difference between protected and unprotected groups	Continuous
Distance To Major Roads (Department of Transport and Main Roads. 2018)	Roads facilitate access and are a known correlate to deforestation (Chomitz and Gray 1999).	Pixels should be matched with the exact same land zone	Continuous
Distance To Watercourses (Department of Natural Resources 2016)	Increased access to surface water increases the likelihood of land development for agricultural or grazing purposes (Apan and Peterson 1998).	Pixels should be matched with the same vegetation type	Continuous
Grass Biomass (Department of Agriculture and Fisheries. 2013)	Lands with higher pasture production are less likely to be protected due to higher production value; vice versa, protected areas will have lower production values on average.	Minimise the mean standardised difference between protected and unprotected groups	Continuous
Shaded Relief (Department of Natural Resources 2013)	Plants and animals both need sunlight to grow and thrive, but access to shade is critical to productivity.	Minimise the mean standardised difference between protected and unprotected groups	Continuous
Land Zones (DSITI 2017b)	Soil and geological characteristics are significant determinates of land arability and therefore decisions around deforestation (Wilson et al. 2005).	Minimise the mean standardised difference between protected and unprotected groups	Categorical; 12 classes
Vegetation Type (Department of Environment and Science. 2017)	The vegetation type is an appraisal criterion for national park selection and specific vegetation categories are more attractive for deforestation (Seabrook, McAlpine, and Fensham 2008), and deforestation is permissible on specific vegetation types (Queensland Government 2018a).	Minimise the mean standardised difference between protected and unprotected groups	Categorical; 16 classes
Rainfall (Booth et al. 2014)	Rainfall is a key determinant of land arability which may lead to competition between protection and production (Nori et al. 2013).	Pixels should be matched with the exact same land zone	Continuous
Slope (Department of Natural Resources 2013)	Flatland (low per cent slope) is easier to clear (Wilson et al. 2005).	Pixels should be matched with the same vegetation type	Continuous
Temperature (Booth et al. 2014)	Temperature is a key determinant of land arability which may lead to competition between protection and production (Nori et al. 2013).	Minimise the mean standardised difference between protected and unprotected groups	Continuous

3.2.5 Pixel Matching

Following multiple trials, I selected a random sample of each bioregional dataset comprising 20% of the total pixels (Wang et al. 2012). The number of pixels assessed varied by bioregion with a maximum of 1.4 million pixels (Brigalow Belt) and a minimum of 22,727 pixels (New England Tablelands) (Appendix 3; **TableA3-1**). I used the MatchIt package (Ho et al. 2018) in R Version 3.3.2 and RStudio 3.3.2 to match protected and unprotected pixels based on their co-variates. Exact matching was used for categorical co-variates (vegetation and landzone), and nearest-neighbour based propensity score matching with replacement for all continuous variables (**Table 3-1**). Propensity scores are a pixel's probability of being treated (protected) based on the baseline characteristics of the co-variates estimated via logistic regression (Rosenbaum and Rubin 1983). Nearest-neighbour matching selects the most similar control (unprotected) pixel for each protected pixel, that with the smallest standardised mean difference from the protected pixel's propensity score. This matching method was selected based on data characteristics: the co-variate distribution was not normal, the sample size was large, the outcome variable (cleared/not cleared) was dichotomous (Imbens and Rubin 2015, Rubin 2006, Ho et al. 2007). All unmatched control pixels are discarded, allowing us to estimate the treatment effects on the counterfactual groups. Matching with replacement allows control pixels to be used as matches for more than one protected pixel and can decrease bias in the estimates of impact (Stuart 2010). Further details on model specifications are provided in Appendix 3.

3.2.6 Quality checks: co-variate balance

I created paired boxplots and used a Man-Whitney U Test to demonstrate the differences between protected and cleared pixels. I then evaluated match balance (co-variate balance) for continuous co-variates using Standardised Mean Difference (M), variance ratios (V), Kolmogorov–Smirnov (KS) test-statistics and Love Plots in the Cobalt package v3.4.1 (Greifer 2018). Using love plots in the Cobalt package v3.4.1, I visualised the MSD in co-variate values for each co-variate within each bioregion (Greifer 2018) based on a random sample of the data before and after the data was matched. Post-matching, M should be as close to zero as possible, but if MSD is less than or equal to 0.25, I considered the balance acceptable (Austin 2009a, Stuart, Lee, and Leacy 2013) according to this metric. Post-matching, V and KS, scores less than or equal to 2 and 0.1, respectively, indicate acceptable balance (Austin 2009a, Stuart, Lee, and Leacy 2013). I report the M, V and KS for each bioregion in co-variate balance tables (**Table 3-2**; Appendix 3: **Table A3-2**). I also compared the similarity of the likelihood of protection (propensity scores) by investigating the distributions of values for protected and matched unprotected (i.e. counterfactual) pixels (Imai and Ratkovic 2014) for all bioregions (**Table 3-2**; Appendix 3: **Figures**

A3-4-A3-24). When distributions overlapped well visually, I inferred the matching method produced a comparable set of counterfactual pixels (Stuart 2010). Lastly, I included additional robustness tests for spatial autocorrelation (**Figures A3-25-A3-34)** and hidden bias.

3.2.7 Quality checks: Hidden bias

The primary assumption of matching is 'ignorability.' Testing for hidden bias ensures that all relevant co-variates have been accounted for in designing the matching algorithm and any other influences can be ignored. If this is violated, estimates of treatment may be influenced by the existence of a significant but unobserved confounder (Stuart 2010, Liu, Kuramoto, and Stuart 2013, Rosenbaum 2002). To quantify hidden bias due to unobserved co-variates on my findings, I used the SensitivityR5 package (Ngendahiman 2017) in R Version 3.3.2 and RStudio 3.3.2 (RStudio Team 2015). In this analysis, I calculated Rosenbaum bounds on estimates of the treatment effect for a range of gamma (Γ) values. In this conservative sensitivity test (Andam et al. 2008), higher gamma values (Γ >1.2) signify that there is no interference on the estimated effect of protection on deforestation by unobserved co-variates (Rasolofoson et al. 2015a) (Appendix 3; (**Figure A3-22**).

3.2.8 Estimating causal impact

To estimate the causal impact of protection on deforestation, I calculated the Average Treatment Effect on the Treated (ATT). This allowed us to assess whether a pixel was likely to have been cleared in the absence of protection by comparing the expected change in forest cover, based on each pixel's propensity for protection (propensity score) and their co-variate values, with the actual change in forest cover (Arriagada et al. 2012, Imbens and Rubin 2015). The ATT was derived using doubly robust methods (Stuart 2010, Stuart and Rubin 2008, Rubin 1973), which use the propensity scores derived from matching as a co-variate (Stuart 2010, Stuart and Rubin 2008). This controls for any remaining imbalance between the co-variates of matched treated and untreated pixels resulting in robust estimates of impact (Rubin 1973) in a process called "regression adjustment" (Imbens 2015, Blackman 2013, Rosenbaum and Rubin 1983).

Regression adjustment is a statistical procedure that uses co-variates which are known to drive deforestation and the propensity score derived from matching as predictors in a logistic model to estimate the probability of deforestation by quantifying the relationship between the co-variates and the outcome (i.e. cleared or not cleared) for each counterfactual and control pixel (Rubin 1973, Guo and Fraser 2014). Regression adjustments were conducted in Zelig v5.1.6 (86, 87) by fitting a weighted logistic regression model to the matched dataset. This model has the form "cleared~ propensity_score + co-variate1+ co-variate2…" To capture any uncertainty in the overall ATT estimate, I computed 1,000 simulations of this model for each bioregion (Horton and Kleinman 2007) (See Appendix 3; **Figure A3-30-A3-31** for further details). Finally, since matching with replacement was utilised, weights were incorporated into the regression to reflect the number of times each counterfactual pixel was used as a match (Stuart 2010).

The average values from the above model were then used to estimate the ATT. The ATT, then, is the mean difference in the expected outcomes (or the values derived from the model) between the protected and counterfactual pixels (see the example from the Brigalow Belt in **Table 3-2**). Negative ATT values suggest deforestation would have occurred if protection was not present. The greater the negative value, the greater the likelihood of deforestation in the absence of protection.

3.2.9 Un-matched (naïve) estimation of the impact

To assess the implications of not performing statistical matching when calculating impact, I used the same subset of randomly sampled pixels (i.e. 20% of a bioregion's total number of pixels) and replicated the approach described above to calculate ATT without statistically matching treated (protected) and control (unprotected) pixels. This generated a naïve (non-robust) estimate of the impact of protection on deforestation (**Table 3-2**).

Table 3-2: Example of impact (ATT) calculation for matched data and a naïve estimate (unmatched data). The values presented here were curated from our Brigalow Belt dataset to represent each category best. For simplicity, only the propensity score is presented for the sample, not individual co-variate data. The expected outcome model (expt.mod) is used to estimate the likelihood that each pixel will be cleared with higher values suggesting a greater likelihood of clearing?. 1Mean expected outcome for protected pixels (rows B & D) minus the mean expected outcome for unprotected, but statistically similar (i.e. counterfactual pixels) pixels (rows A&C). 2Mean expected outcome for protected pixels (rows B & D) minus the mean expected outcome for all unprotected pixels (rows A, C, E-H).

Label	Protected (Y="1", N= "0")	Cleared (Y="1", N= "0")	Propensity score (%)	Expt.mod (%)	Category
A	0	0	82	$4.94*10^{-4}$	Counterfactual pixel
B	1	0	75	0.94	Protected, not likely to be cleared
C	0	0	80	1.06	Counterfactual pixel
D	1	0	27	0	Protected, not likely to be cleared
E	0	1	6	55	Not protected, not likely to be protected, likely to be cleared
F	0	0	1	14	Not likely to be cleared, not likely to be protected and neither cleared nor protected
G	0	1	1	21	Cleared, not likely to be protected
H	0	1	3	36	Cleared, not likely to be protected
Mean outcome		0.4			
ATT.Matched[1]				-0.06	
ATT.Un-matched[2]				-20.21	

3.2.10 Calculating the area of avoided deforestation

Finally, I used the mean impact estimate for the matched and unmatched data (King, Tomz, and Wittenberg 2000) to estimate the total area of avoided loss (km^2) attributable to protected areas (Rasolofoson et al. 2015b). I did this by multiplying the bioregion's estimated impact (%) by the total area within each bioregion that had been cleared since 1988 (Miteva et al. 2019, Jusys 2018).

3.2.11 Quality checks after estimating causal impact: spatial autocorrelation

Spatial autocorrelation occurs when similarity in biophysical characteristics is related to geographical proximity, thereby violating the assumption of independence (i.e. co-variate values are location-dependent). If spatial autocorrelation has caused the causal impact model to perform well for certain areas of the study zone, but poorly for others, then mapping the model's residuals can help determine which areas are worst affected (Pebesma 2018). An assessment of spatial autocorrelation is best practice in conservation planning (Schleicher, Eklund, et al. 2019a) because of a failure to account for spatial autocorrelation risks over or underestimating the impact (Dale and Fortin 2009). By randomly selecting protected and non-protected pixels, I attempted to reduce the effects of spatial autocorrelation in my analyses (Rasolofoson et al. 2015a). While previous studies suggest that random sampling may be reduced by sampling ensuring that the distance between sampling pixels is at least the length of one pixel (Andam et al. 2008), this method has not been applied across a variety of landscape types and its associated habitats. Rather than assume that spatial autocorrelation is reduced by sampling in this way, I use a randomly sampled dataset and test for spatial autocorrelation. I then discuss the implications of spatial autocorrelation and its implications for the results and for future studies.

I tested for potential spatial autocorrelation for the random and matched samples using Moran's I- a well-established statistical metric of spatial autocorrelation (Getis 2008). I also checked how well random sampling reduced spatial autocorrelation by mapping the residuals of the propensity score model against the pixel's central coordinate using Bubble Plots (Pebesma 2018) for matched and randomly sampled data (*i.e.* before and after matching). For both datasets, I inspected trends in bubble clusters according to the size or colour of the bubbles. These trends indicate where spatial autocorrelation might occur, and if matching reduces or amplifies this trend (Oldekop et al. 2019). I found that spatial autocorrelation was present in both datasets. Caution is needed when interpreting the Moran's I and the residual bubble plots. In their application to spatial econometric models (such as the ATT estimate), some suggest that can be due to the spatial proximity of deforestation drivers, and not necessarily similarity among the deforestation rates (Jackson et al. 2010) (Appendix 3; **Figures A3-22-30**). Furthermore, because matching is attempting to statistically similar pixels and before similarity is known to be influenced by proximity, matching may increase the presence of spatial autocorrelation. More research is needed to better understand its influence in such instances, and I explore the role of spatial autoregressive models in Chapter 5.

3.3 Results

3.3.1 Characteristics of protected areas

I found notable differences in the biophysical characteristics (co-variates) between cleared and protected pixels. Specifically, protected pixels were further from built-up areas, had a lower grazing capacity (grass biomass), and occurred on steeper slopes. Cleared areas tended to be closer to roads, have a higher temperature and have a lower rainfall. Cleared and protected pixels were similarly close to watercourses. Overall, I found that the majority of co-variates were statistically dissimilar ($p<0.05$) except for shaded relief ($p = 0.58$) (**Figure 3-3**).

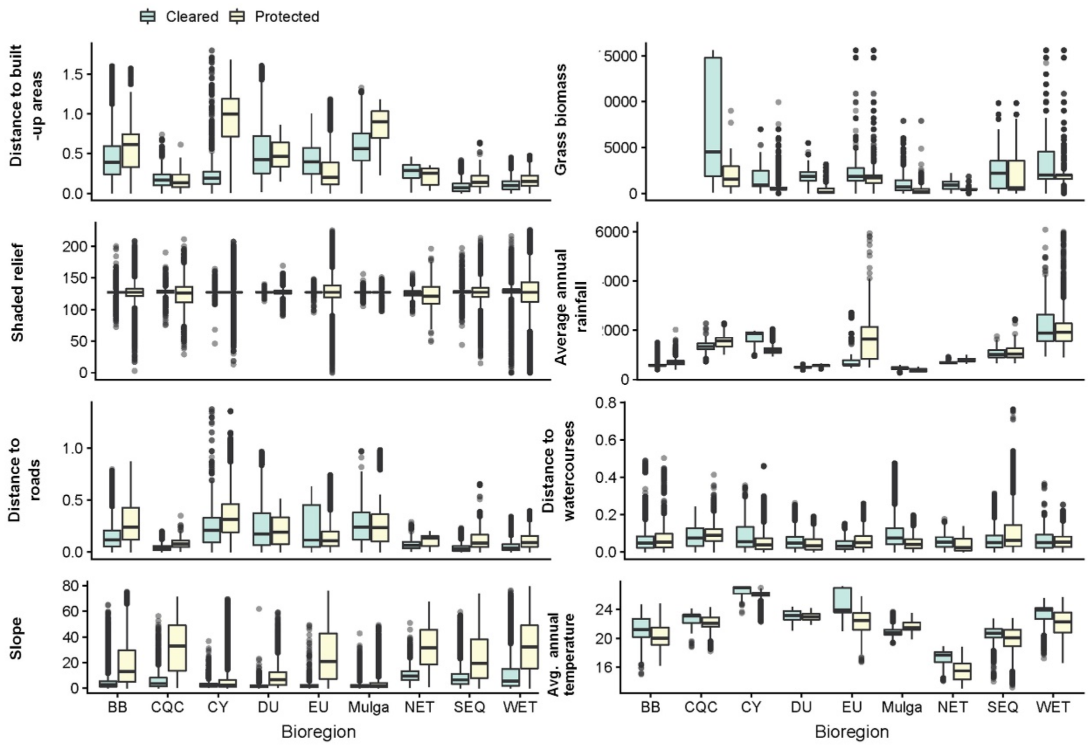


Figure 3-3: Boxplots showing the differences biophysical characteristics of in cleared vs protected pixels for the study regioneach bioregion. BB = Brigalow Belt, CY = Cape York, CQC= Central Queensland Coast, DU = Desert Uplands, EU = Einasleigh Uplands, MU = Mulga Lands, NET = New England Tablelands, SEQ = Southeast Queensland, WET = Wet Tropics

3.3.2 Pixel matching and co-variate balance

Despite differences in protected and unprotected groups before matching (**Figure 3-3**; Appendix 3), I was able to match between 99-100% of protected pixels in all bioregions to equivalent unprotected pixels (Appendix 3: **Figure A3-3**). For all co-variates and bioregions, a minimum of one of the statistical balance thresholds was met, but the majority met more than one. An in-text exemplar of tabulated balance metrics for the Brigalow Belt is shown in **Table 3-3**. Of the covariates included in each bioregion, 27.7% did not meet a conservative threshold of 0.1 for standardised mean differences; however, 97% met a less conservative threshold of 0.25 (**Figure 3-4; Table 3).** Metrics for all other bioregions are provided in Appendix 3; **Table A3-2**.

Table 3-3: Example of co-variate balance table using results from the Brigalow Belt. This table shows the co-variate name, the mean of the unprotected pixels from the random sample (Mean.Not-protected.Random), mean average of the protected pixels from the random sample (Mean.Protected.Random) and their mean standardised difference (MSDDiff.Ran). It then shows the mean average of the unprotected and protected pixels after matching (Mean.Not-protected.Matched, Mean.Protected.Matched), and their mean standardised differences after matching (Diff.Adj). The values for the matched test-statistics include variance ratios (V) and Kolmogorov–Smirnov (KS) thresholds. For each threshold, a "^" is given next to the value if it is acceptably balanced

Co-variate name	Mean Unprotected Random	Mean Protected Random	MSD Random	Mean Unprotected. Matched	Mean Protected Matched	MSD Matched	V.	KS
Dist. To built-up areas	0.38	0.57	0.68	0.57	0.57	-0.014^	1.18^	0.08^
shaded relief	126.88	126.30	-0.03	126.46	126.30	-0.01^	1.37^	0.05^
Rainfall	627.01	697.05	0.50	686.30	697.05	0.08^	1.23^	0.08^
dist to road	0.13	0.29	0.73	0.29	0.29	-0.03^	1.10^	0.05^
Slope	6.58	18.90	0.71	19.078	18.90	-0.01^	1.01^	0.01^
dist to watercourse	0.06	0.073	0.14	0.07	0.07	0.02^	1.00^	0.04^
Temperature	21.16	20.34	-0.48	20.39	20.34	-0.03^	1.03^	0.06^

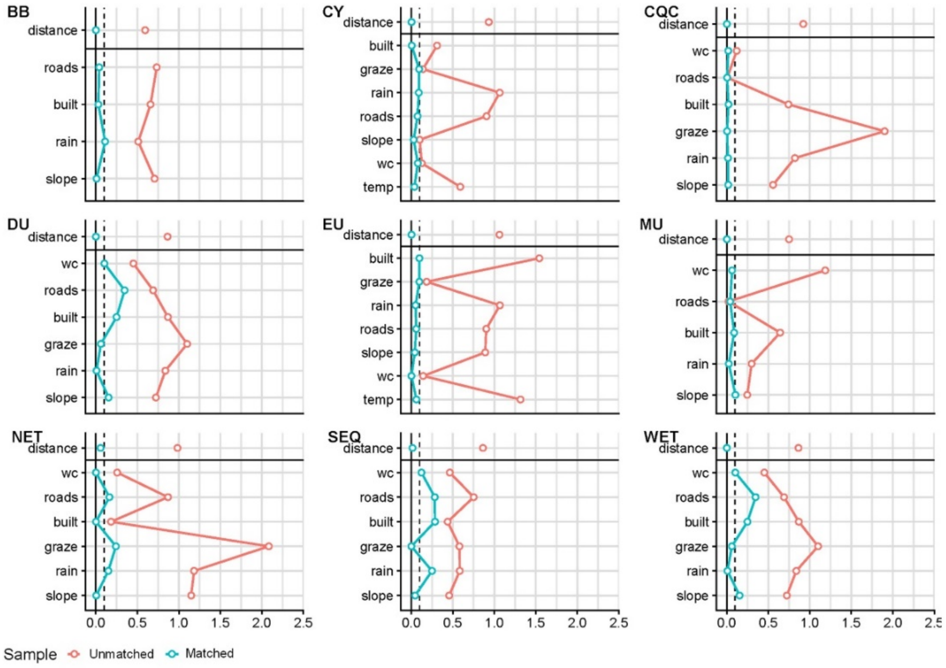


Figure 3-4: Love plots diagnose balance for each bioregion. Love plots show the standardised mean difference of co-variates prior to and after matching (Unmatched, Matched). Love plots illustrate the standardised mean difference between protected and unprotected pixels before and after matching. The dotted line is a conservative mean differences conservative threshold of 0.1 – though values up to 0.25 are acceptable. In these plots, the variable "distance" is the propensity score. Unadjusted values are the standardised mean differences before matching, and adjusted values are the standardised mean. BB = Brigalow Belt, CY = Cape York, CQC= Central Queensland Coast, DU = Desert Uplands, EU = Einasleigh Uplands, MU = Mulga Lands, NET = New England Tablelands, SEQ = Southeast Queensland, WET = Wet Tropics.

Similarly, the variance ratio was less than two for the majority (97%) of co-variates. However, 58% of co-variates failed to meet the Kolmogorov-Smirnov threshold. I concluded that my matching algorithms performed well in eliminating non-comparable pixels, but, given the poor performance against the Kolmogorov-Smirnov threshold, I performed a regression adjustment. I found that all my results were robust to hidden bias, and I found that deforestation is spatially autocorrelated (See supporting information (**Table 3-3**; Appendix 3).

3.3.3 Comparing measures of avoided deforestation

Without matching, the estimate of avoided deforestation across all bioregions was 25% –double the matched estimate (10.5% matched **Table 3-4**). For individual bioregions, I observed significant differences in the estimated ATT when comparing the unmatched and matched approaches. In general, the mean ATT was almost always higher before matching (Cape York being an exception). Before matching, 7.32% of deforestation which occurred between 1988 and 2018 was avoided because of protection. After matching, the highest mean ATT estimate was again observed in the Brigalow Belt but was reduced (2.60%). The lowest per cent of avoided deforestation after matching was observed in the Wet Tropics bioregion (0.26%).

Outliers or Average Treatment Effect on the Treated (ATT) estimates above the first and third quartile, were present for all bioregions. Significantly, the ATT estimates in the New England Tablelands (NET) ranged from -0.07% to -6.70%, giving this bioregion a more comprehensive range than others considered in this study. I attribute the cause of the outliers to the extensive deforestation (McAlpine et al. 2002; Queensland Department of Environment and Science 2019) and a small area under protection in the bioregion (28km^2). I, therefore, presented the estimated ATT for NET, but caution that outliers influence the mean, possibly decreasing the accuracy of these estimates.

Table 3-4: Average Treatment Effects on the Treated (ATT) for each bioregion. Results are presented for unmatched and matched. We also show the area of avoided deforestation in km^2 as estimated with matching. Estimates of avoided deforestation (km^2) were calculated by multiplying total protected area in the bioregion between 1988 and 2018 by the Mean ATT (%). ‡signifies a significant difference in mean ATT of the matched and unmatched datasets at the 5% level (p-value ≥ 0.05).

	Mean ATT Unmatched	Mean ATT Matched	Area protected (km^2)	Per cent Protected	Area cleared (km^2)	Per cent of area cleared^	Avoided (km^2)
Brigalow Belt ‡	-7.32%	-2.60%	6,319	1.72	41,337	11.6	-164.3
Cape York ‡	-0.17%	-0.78%	14,651	11.9	347	0.3	-111.4
Central Queensland Coast ‡	-1.37%	-0.84%	623	4.20	458	3.7	-5.2
Desert Uplands ‡	-3.51%	-1.26%	1,720	2.46	5,523	9.1	-21.7
Einasleigh Uplands ‡	-0.82%	-0.37%	2,463	4.81	2,327	1.0	-9.1
Mulga Lands ‡	-4.31%	-1.42%	5,091	2.73	16,438	9.7	-72.3
New England Tablelands ‡	-2.92%	-1.38%	154	1.97	508	7.1	-2.1
Southeast Queensland ‡	-3.64%	-1.60%	6,843	10.85	2,877	4.6	-109.5
Wet Tropics ‡	-0.88%	-0.26%	8,747	44.13	375	2.2	-22.7
Total	-24.94%	-10.51%	46,611		70,190		-518.4

3.3.4 Estimates vary between bioregions

The overarching characteristic of the study region was that highly cleared areas tended to have minimal protection, and highly protected areas tended to have minimal deforestation (**Table 3-4).** Resultantly, there was variation in the ATT estimates across bioregions, both before and after matching. For example, after matching, the highest ATT estimates were observed in the Brigalow Belt (-2.60%), Southeast Queensland (-1.60%), and the Mulga Lands (-1.42%). The lowest estimated ATT was observed in the Wet Tropics (-0.26%). The mean ATT was less than 1% for five of the nine bioregions in the study area (Cape York, Central Queensland Coast, Einasleigh Uplands, New England Tablelands, and the Wet Tropics) (**Figure 3-5**). Such low estimates indicate that protected areas had almost no effect in avoiding deforestation compared to unprotected areas in these bioregions.

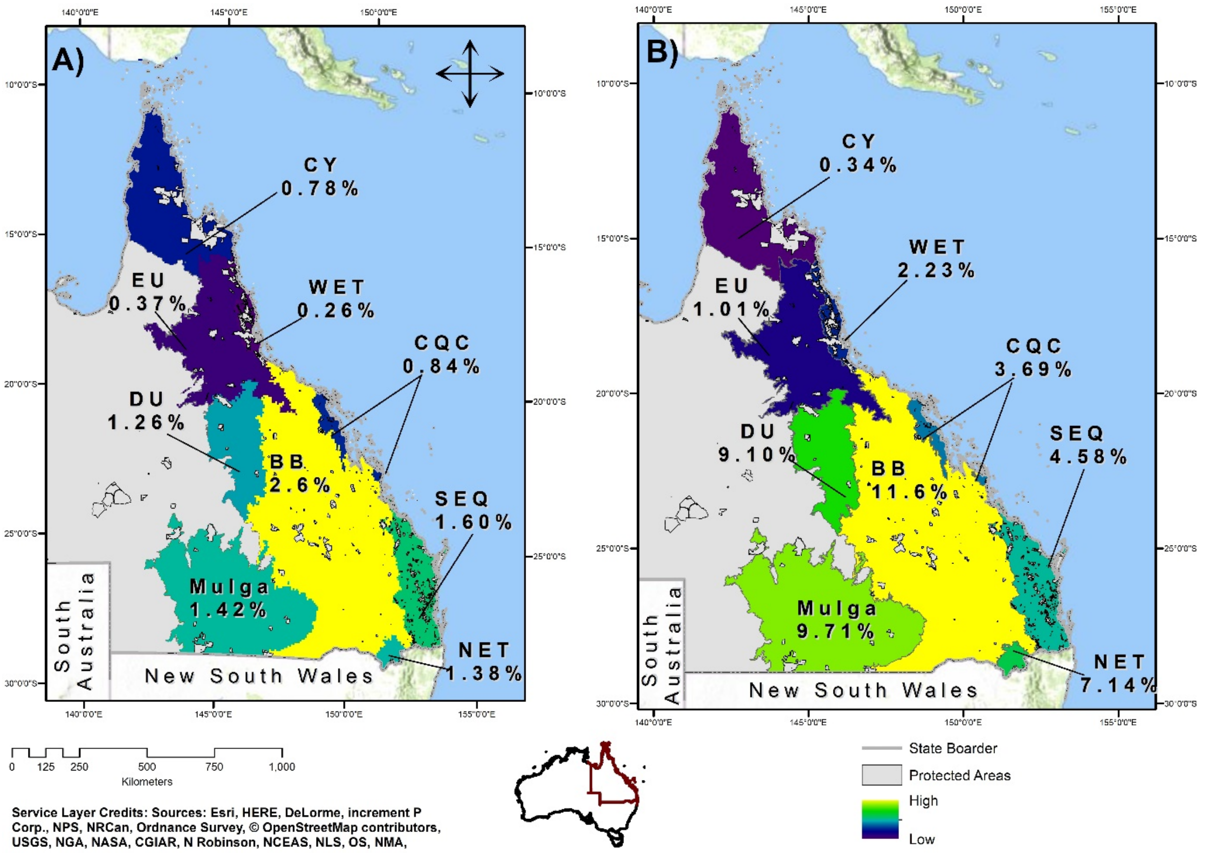


Figure 3-5: Maps of the study area showing the variation in impact (A) and the per cent of land that has been cleared from 1988 to 2018 (B). Brigalow Belt (BB), Cape York (CY), Central Queensland Coast (CQC), Desert Uplands (DU), Einasleigh Uplands (EU), Mulga Lands (Mulga), New England Tablelands (NET), Southeast Queensland (SEQ) and Wet Tropics (WET). The per cent of the bioregion that has been cleared since 1988 is shown underneath the bioregion name.

Between 1988 and 2018, 70,190 km^2 (49.4 %) of land was cleared in the study region. I estimated that 518 km^2 (or 96,800 football fields) of deforestation was avoided because of protected areas across the study region (which cover 974,907 km^2 or approximately than 182,184,232 football fields). Of this, most of the avoided deforestation was 1,075 km^2 (200,889 football fields) in the Brigalow Belt. The smallest area of avoided deforestation was approximately 0.96 km^2 in the Wet Tropics (**Table 3-3**). In total, this means that 10.5 per cent of land in protected areas would have been cleared in the absence of protection. Put differently, 89.5% of the protected areas included in this study would not have been cleared even if they were never protected.

3.4 Discussion

Statistical matching approaches correct estimate impact because they control for confounding variables. Confounding variables mask conservation program failure or mimic conservation success and are not uniformly distributed across landscapes (Joppa, Loarie, and Pimm 2008). Indeed, I found that within the Queensland context, there were differences in the landscape characteristics between protected and cleared pixels. Protected pixels tended to have characteristics that were less favourable for agricultural development (*e.g.* higher slope). This result is consistent with previous studies demonstrating the non-uniformity of protected pixels across landscapes (Joppa and Pfaff 2010b). Considering this finding, a failure to use statistical matching risks over-estimating the impact of protected areas in Queensland. When comparing statistical matching approaches to a naïve estimate, I found that the naïve estimate overestimated impact by as much as 50%. This result is consistent with extensive literature regarding the use of statistical matching for estimating impact (Rasolofoson et al. 2015a, Nolte, Agrawal, and Barreto 2013, Bruggeman, Meyfroidt, and Lambin 2015, Andam et al. 2008).

While other studies have considered the impact of protected areas at a state or national scale, our study uniquely examines impact by bioregion. In Queensland, the extent of deforestation per bioregion is not uniform (with between 0.34% and 11.6% of each bioregion cleared). Performing a per bioregion analysis provides insights to the drivers of deforestation at socio-economic and biologically relevant spatial scales that would have otherwise been unobserved. For example, I observed significant variation in ATT estimates across bioregions (**Table 3-4; Figure 3-5**). The highest ATT was observed in the Brigalow Belt (2.6%). The Brigalow Belt, named Australia's most ecologically transformed area (Ponce Reyes et al. 2016), is heavily impacted by grazing activities. With 11.6% of the bioregion cleared between 1988-2018 and over 30% cleared since European settlement (Neldner, Laidlaw, et al. 2017), this bioregion has experienced the highest deforestation rates in recent years (Queensland Department of Environment and Science 2018).

Likewise in South-east Queensland, where a long history of development has resulted in a profoundly transformed landscape (Neldner, Laidlaw, et al. 2017), our results demonstrate that less than 2% of protected areas would have been cleared in this bioregion in the absence of protection. Low impact estimates in profoundly transformed bioregions reinforce extensive literature regarding the “residual bias” of protected areas.

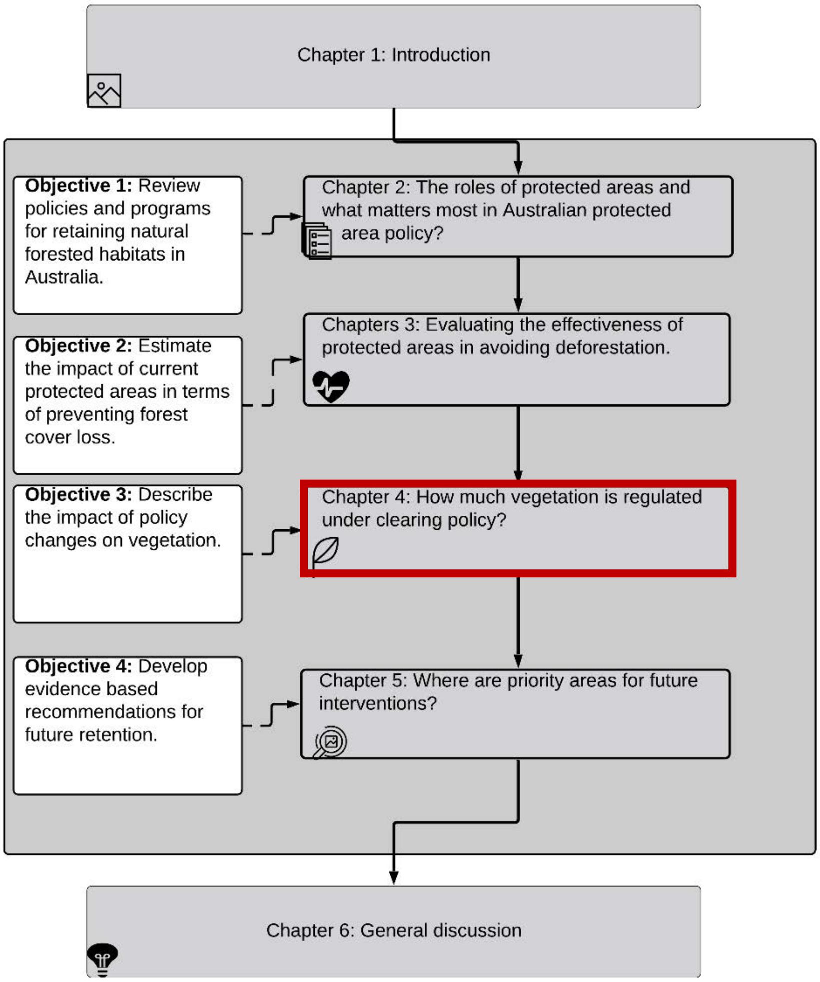
In contrast to low impact of protected areas in highly cleared bioregions, I also found low impact in relatively intact bioregions. For example, in the Cape York Peninsula only 0.38% of its area has been deforested since 1988 and received an ATT score of 0.78% (**Figure 3-5**). This bioregion contains vast and relatively undisturbed landscapes that support extraordinary ecological and Traditional Owner heritage values (Hitchcock et al. 2013). Clearing, however, is an emerging threat to this bioregion as it is targeted for future development under a Federal commitment to increase agricultural outputs in Northern Australia (Taylor, Payer, and Brokensha 2015, Commonwealth of Australia. 2015). It is possible that incorporating the likelihood of deforestation into protected area selection will help future protected areas make measurable contributions toward achieving the globally agreed goal of halting deforestation (United Nations 2018). The next few years present a new opportunity to acquire high impact protected areas that mitigate likely deforestation in Cape York.

Protected areas with low estimates of avoided deforestation in regions where deforestation rates are low may have a high impact for other metrics because there are other protected area objectives. For example, I observed the lowest estimate of impact in the Wet Tropics bioregion (0.26%). This mountainous and species-rich bioregion has, by per cent of total area, the largest protected area network (44.13%), and while relatively small in total area deforestation (2.23%) in fertile regions of this bioregion has resulted in a highly fragmented landscape (Neldner, Laidlaw, et al. 2017). Large portions of the protected area estate in the Wet Tropics safeguards the remnant and topographically complex rainforest habitat and its highly endemic fauna (Commonwealth of Australia 1986) as World Heritage Areas (Liburd and Becken 2017). This has successfully prohibited selective logging (Laurance 1994) and, through government reforestation incentives (Harrison, Wardell-Johnson, and McAlpine 2003), attempts to reverse the long-established adverse effects of logging on biodiversity (Nepstad et al. 1999, Asner et al. 2005). Our analysis does not address the impact of protected areas in reducing selective logging, because the spatial resolution of the remotely sensed satellite data is insufficient to measure selective timber harvest. Impact estimates might be higher with consideration given to this process. For these reasons, the Wet Tropics bioregion is expected to have a low impact estimate.

3.5 Conclusions

Since 1988, the strictly protected area network in the study area tripled in the area (13,480 km^2 in 1988 to 46,611 km^2 in 2018), with the primary objective of conserving biodiversity by avoiding and managing threatening processes (Queensland Government. 2017). In this period, total deforestation in the considered bioregions was 57,488 km^2 or about 10.7 million football fields. Despite this growing threat, I found that 89.5% of land in protected areas would not have been cleared even in the absence of protection. The estimated impact was highly variable between bioregions. Regions with more development had a higher impact but are still much lower than expected given deforestation rates. Regions with moderate to little development had close to zero impact. These results demonstrate that strictly protected areas are not guarantees of effective reduction in deforestation because protected areas are biased towards areas with a low propensity for clearing. The results of this analysis support recommendations for outcome-based targets (Visconti, Butchart, Brooks, Langhammer, Marnewick, Vergara, Yanosky, and Watson 2019) focused on avoiding threatening processes (Sacre et al.). Using rigorous evaluation measures for conservation interventions, we can quantify the impact of conservation interventions leading to measurable outcomes for biodiversity

Chapter 4. The consequences of rapid policy change for assessable vegetation.[3]



[3] This chapter is based on a journal article in preparation for *Australasian Journal of Environmental Management*

Abstract

Habitat loss is a significant driver of species extinction. The policies which control habitat loss are essential determinants of biodiversity outcomes. Using Queensland as a case study, I demonstrate the implications of policy changes in terms of increased or decreased vegetation available for clearing without a permit. I achieve this by analysing the regulatory framework for Queensland's Vegetation Management Act, 1999 (the Act), which is the primary Act governing land clearing. In 2013 and 2018, there were substantial amendments to the Act. I evaluated these changes by assessing the state-wide implications, in terms of increased or decreased exposure of vegetation to clearing. I then comment on the estimated extent of vegetation impacted by these changes. Thus, I explored three variants of clearing guidelines: *strict:* guidelines from 2012*, relaxed* guidelines from 2013 and *modern* guidelines from 2019*.* Between the strict and relaxed guidelines, I identified six policy changes with significant implications for vegetation management. The most significant change was introducing permissions to clear native vegetation for agricultural and pastoral production. Under the relaxed guidelines, 78 million ha of remnant vegetation was made available for clearing for agriculture or grazing purposes. Furthermore, policy changes resulted in increased exposure of vegetation in wetlands and rivers by over 2 million ha. Between the relaxed and modern scenarios, I identified five policy changes with significant implications on vegetation management. One significant change was the revocation of the permission to clear to establish broad-acre cropping or grazing properties. The second was the removal for thinning as a relevant clearing purpose. In seven years, clearing policies changed enormously with significant consequences for vegetation. As demonstrated here, failing to consider the ecological effects of rapid policy change underestimates the total impact of policy change on vegetation and such evaluations are currently not required before policy change.

4.1 Introduction

Broad-scale clearing refers to the extensive removal of woody vegetation and its permanent or semi-permanent conversion to a non-vegetated land use, but, typically does not include legislatively prescribed maintenance activities (McGrath 2007) Clearing is a consequence of interconnected dynamics of human populations and their economics, scientific and technological developments, cultural values, and policies (Seabrook, McAlpine, and Fensham 2006, 2008) (Lambin, Geist, and Lepers 2003, Lambin and Meyfroidt 2011). The consequences of land clearing for the environment include: reducing the extent and abundance of species (Haddad, Brudvig, Clobert, Davies, Gonzalez, Holt, Lovejoy, Sexton, Austin, and Collins 2015), habitat fragmentation (Holland and Bennett 2010) and decreased efficiency and functionality of ecological processes (Cogger 2003). In Australia, substantial clearing of native vegetation has occurred on arable lands for agricultural and pastoral production (Evans 2016, McAlpine et al. 2009). The majority of land clearing in Australia occurred in the last 50 years in the State of Queensland (**Figure 4-1**) (Bradshaw 2012). For example, in the four years between 1991 and 1995, Queensland was responsible for 80% of the 1.2 million ha cleared across Australia (Accad and Neldner 2015, Wilson, Neldner, and Accad 2002). Between 2001 and 2003, clearing of woody vegetation in Queensland reached levels of over 1.05 million ha per year (0.56% of Queensland's total area).

Australia's ratification of the United Nations Convention on Biological Diversity (UNCBD) in 1993 resulted in a cross-jurisdictional enterprise to curb vegetation loss. For example, Federal funding could be accessed in return for meeting national standards on vegetation cover. As a result, Queensland passed the Vegetation Management Act in 1999 (hereafter, the Act) to address concerns over the effects of broad-scale clearing of native vegetation, encourage ecologically sustainable use of land, and maintain regional biodiversity. The primary intent of the Act is to avoid land degradation and maintain biodiversity and ecological processes. The Act achieves these goals by regulating land clearing on two broad categories of vegetation: vegetation which has never been cleared (remnant vegetation) and vegetation which has previously been cleared but has been allowed to regrow approximately thirty years (high-value regrowth).

4.1.1 Vegetation management terminology

For the two categories of vegetation mentioned above, the Act outright prohibits some areas from clearing or allowing clearing in other areas following a development application. If proposed clearing does not comply with the guidelines, then a development application is required. In general, one component of a development application. According to the Act, vegetation in areas which triggers a development application is called assessable vegetation. Vegetation which does not trigger a development application is called nonassessable vegetation.

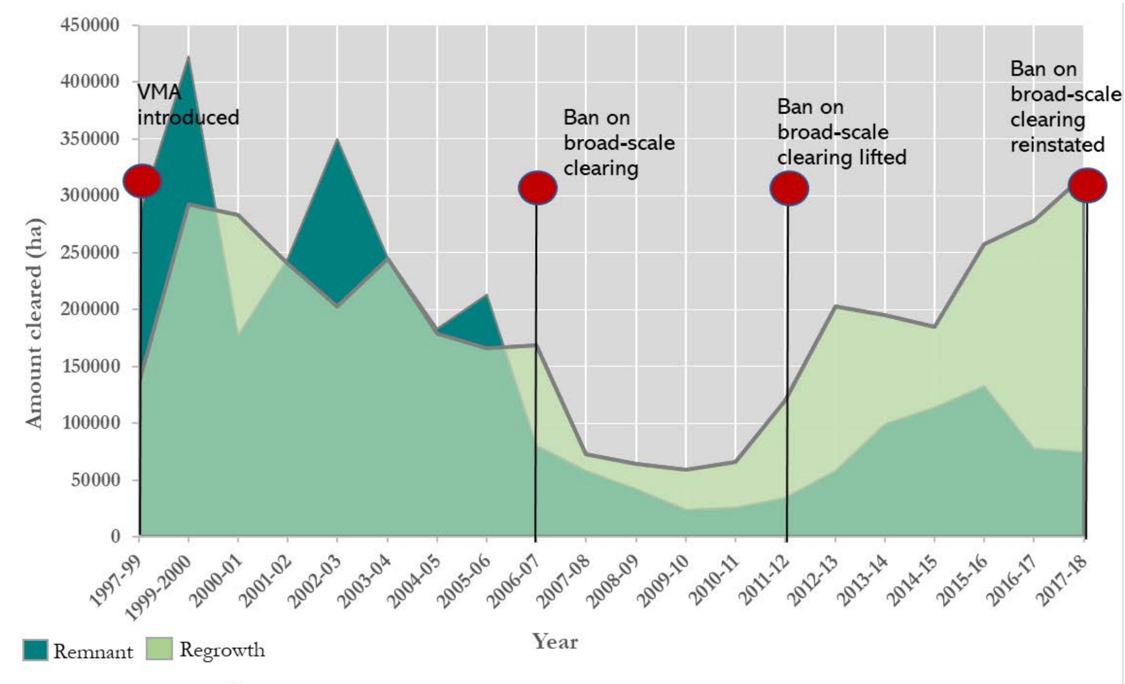


Figure 4-1: Amount (ha) of remnant woody vegetation cleared each year. I sourced data from (Queensland Department of Environment and Science 2018). Graph adapted from (Taylor 2013).

The Act was widely accepted as an effective policy for managing land clearing but has been called controversial as it attempts to marry the needs of rural landholders and biodiversity conservation. Following the prohibition of broad-scale clearing under the Act in 2006, clearing rates per year fell by over 200,000 ha between 2006 and 2010, marking a historic low for clearing rates in Queensland (Government. 2015a, DSITI 2017b) (**Figure 4-1**). In 2013, however, the Act was amended, allowing for the resumption of broad-scale clearing for high-value dryland and irrigated agriculture as part of a government initiative to expand agricultural development. In the years that followed, Queensland's rate of deforestation soared to over 350,000 ha per year (Government. 2015a). Recent statistics now show that Queensland's rate of deforestation is nearly 400,000 ha per year, making the State a global deforestation hotspot (Hudson 2019) (**Figure 4-1**). As a result of this extensive and on-going clearing, many vegetation communities in Queensland are vulnerable to extinction (Tulloch, Barnes, et al. 2015). Such a marked change in clearing rates has serious implications for biodiversity and may be attributable to policy changes. Queensland, therefore, represents an ideal case study for understanding how policies affect land clearing.

Previous studies have commented on the substantial effects of rapid policy change on vegetation management in Queensland. For example, Taylor (Taylor 2013) estimated that 1.3 million hectares of previously uncleared vegetation would be placed at risk of future clearing following the 2013 changes to the Act. In addition to the total extent of vegetation at risk, a 2017 study also found that the Act fails to protect the forest types experiencing the highest clearing rates (Rhodes et al. 2017). Like Taylor's findings, another recent study evaluated the impact of vegetation policy in Queensland and found that the Act was largely ineffective at curbing deforestation (Simmons et al. 2018).

The research presented here furthers previous studies by investigating one potential reason the Act has been evaluated as ineffective, namely variations associated with the guidelines. I do this by analysing the guidelines which support the outcomes of the Act and aim to compare the potential consequences for variations of the guidelines by summarising the cumulative potential impact of policy changes. I focused on the following time-steps: 2012-2013 and 2014-2015, and 2019. I chose these years because the 2013 and 2018 amendments to the Act were a substantial overhaul of vegetation management, providing an exemplar of rapid policy oscillation. For each time step, I summarised and described the fundamental policy changes that have resulted in increased or decreased exposure to land clearing concerning biophysical or geological features regulated by clearing guidelines. I further this by providing maps and area summaries that evaluate two scenarios (*strict* and *relaxed*). These two scenarios bound the possible range out outcomes (in terms of the area available for clearing). By analysing clearing guidelines in this way, this research demonstrates the fundamental importance of comparative policy analysis to inform future decision making.

4.2 Methods

4.2.1 Overview

A proposed development in Queensland may fall into one of three categories: accepted, prohibited and assessable (England 2016). Accepted development is, generally, low risk in nature because it does not have any significant impact on the environment or neighbourhood. Accepted development does not require an application or approval. Prohibited development is not permitted under any circumstances (Queensland Government 2020). Assessable development requires a developer to submit an application demonstrating compliance with relevant regulations and codes. For example, Queensland's Vegetation Management Act 1999 has supporting guidelines, called "clearing codes," for permissible vegetation clearing. Clearing within 20m of a major watercourse is a current benchmark within the codes (Queensland Government 2019a). If the proposed development cannot demonstrate compliance with this benchmark, then the noncompliant part of the application can be denied or approved with conditions. Approval with conditions is integrated into an "Environmental Authority" held by the proponent and subject to regular audits by State or local governments (England and McInerney 2017).

Assessable development requires government assessment and approval. In Queensland, there is a range of factors that may trigger an assessment at multiple levels of government (*ie* Federal, State and local). This process uses an environmental impact statement (EIS). An EIS describes the nature and extent of potentially impacted environmental values and what actions are necessary for the project design or operation to avoid, manage or mitigate adverse impacts. At the Federal level, an EIS can be triggered if the proposed activity will significantly impact features regulated under the *Environmental Protection and Biodiversity Conservation Act 1999 (EPBC).* Biodiversity features regulated by the EPBC are called matters of national environmental significance (MNES). To determine if the impact is significant, the activity is assessed under significant impact guidelines (Australian Government 2013). At the State level, an EIS process can be required if the proposed development will have impacts on a biodiversity asset regulated in one or more pieces of legislation: *Nature Conservation Act 1992*, *Marine Parks Act 2004*, *Fisheries Act 1994*, *Environmental Protection Act 1994, Regional Interests Planning Act 2014 or the Vegetation Management Act 1999* (for a summary of this process, see **Appendix 1**).

Comparative policy approaches examine the similarities and differences between policies either across nations or sub-nations or through time (Fischer and Miller 2017, Ciccia and Javornik 2019) and are often used to inform future policy development. Publicly available clearing guidelines (hereafter, guidelines) describe the biophysical and landscape features which trigger the regulation under the Act. Proponents of clearing are required to comply with the guidelines. Guidelines are indicative of likely clearing because they describe an appraisal framework purposed with fulfilling the biodiversity outcomes declared in the Act (*i.e.* conserves remnant vegetation that is an endangered ecosystem). I gathered historical clearing guidelines from 2012-2013 (before amendments to the Act re-permitted broad-scale clearing) and 2014-2015 (after the Act was amended and the guidelines reflected these changes), and 2019 (after further amendments to the Act which, again, prohibited broad-scale clearing and the guidelines reflected these changes). Hereafter, I refer to clearing guidelines collected from 2012-2013 as *strict,* guidelines collected from 2014-2015 as *relaxed* and guidelines from 2018-2019 as *modern*. I used the following four-step process to identify (**Figure 4-2**) and describe changes in the guidelines using a comparative policy approach.

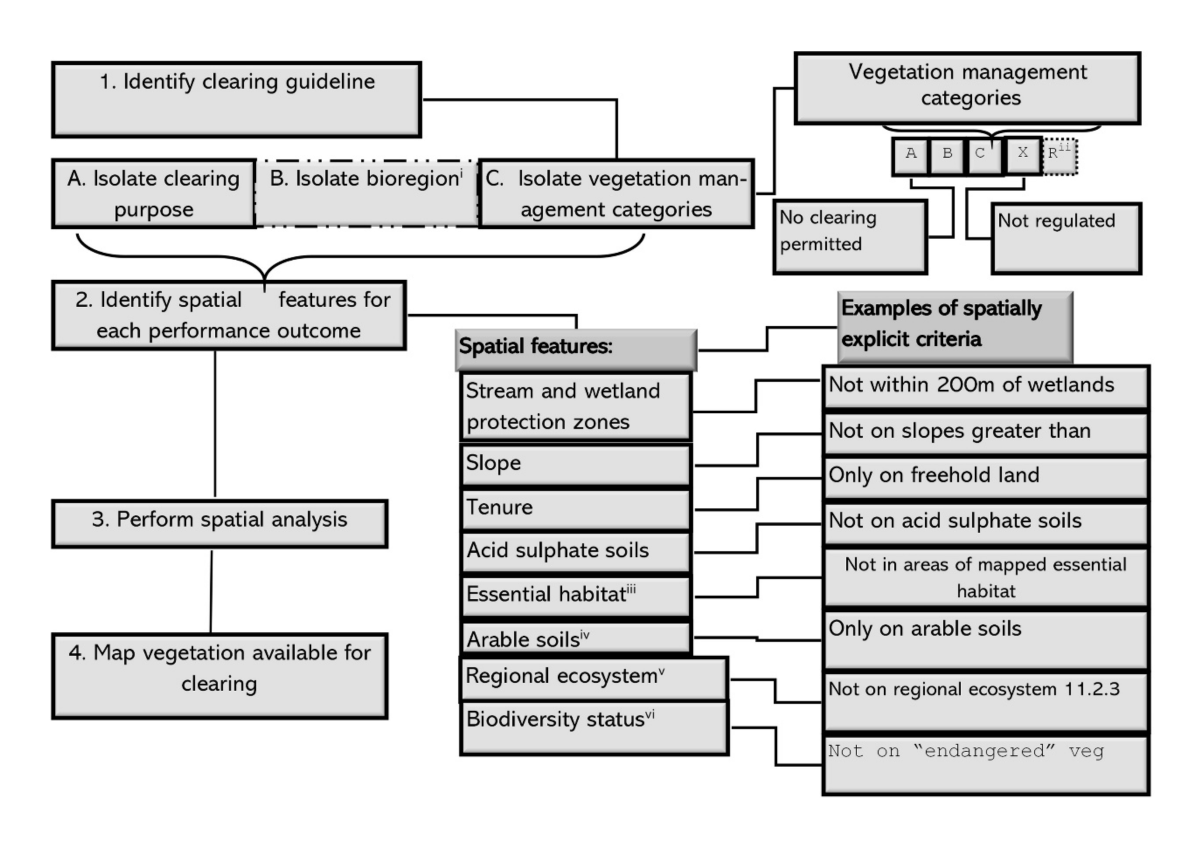


Figure 4-2: Interpretation of clearing guidelines to produce summaries of clearing guidelines for each purpose. [i]Strict scenario only. [ii] Relaxed scenario only [iii]Vegetation in which a species that is Endangered or Vulnerable under the Nature Conservation Act (1992) occurs. [iv]Land classified as having potential for agricultural development (Department of Agriculture and Fisheries 2014). [v]See Glossary for the definition of regional ecosystems [vi]Biodiversity status categories are endangered, of concern, or least concern (Glossary).

4.2.2 Step one: identify relevant clearing guidelines

Clearing guidelines either corresponded to regions, vegetation management categories, and clearing purposes (*strict*) or simply vegetation management categories and clearing purposes (*relaxed*). I obtain guidelines for the *strict* and *relaxed* scenarios directly via email from the Department of Natural Resources and Mines (DNRM). For the *modern* scenario, I obtained clearing guidelines directly from the department's website (https://www.dnrme.qld.gov.au). I consulted with officers responsible for monitoring clearing compliance across the State. I produced a summaries of my understanding of each spatial restriction on clearing for each guideline and under each purpose. The Officers reviewed these summaries and changes were applied if needed.

4.2.3 Step two: isolate clearing purpose

In the guidelines, clearing purposes are also called management purposes or operational works and relate to the reason a proponent may want to clear vegetation. To maintain consistency, I use “clearing purposes” to refer to any clearing activity that is regulated by clearing guidelines and is enforceable under the Act. I comprehensively reviewed all guidelines and identified the clearing purposes therein. I excluded clearing purposes which related to single, one-off clearing events or environmental clearing (clearing to build a shed or clearing to manage weeds). In this study, I considered five clearing purposes described in the guidelines:

1. **Agricultural and grazing:** broad-scale clearing to establish new areas for high-value agriculture or irrigated high-value agriculture on fertile soils or broad-scale clearing to develop new areas for cattle production (limited to areas on grazing leases);
2. **Extractive industry:** the clearing of vegetation to establish mines;
3. **Encroachment**: the removal of native woody plants, gidgee, *Acacia sp.*, and false sandalwood (*Eremophila mitchellii*), from grasslands to allow for native grass regeneration for pasture;
4. **Fodder harvesting:** selective harvesting of tree species for stock feed;
5. **Thinning:** selective removal of trees to reduce them to a density specified for the ecosystem.

I do not consider urban expansion in this study because urban expansion is not a clearing purpose for which there is a guideline under the VMA. Clearing for urban expansion is under the remit of local councils (Local Government Areas). A separate study considering the guidelines for urban expansion is needed.

4.2.4 Step 3: isolate bioregion

Strict guidelines corresponded to bioregions or groups of bioregions. I applied Steps 2-4 after spatially isolating vegetation within the boundaries of the bioregions. Isolation by bioregion only applies to the *strict* scenario and is therefore outlined with a dashed line in Figure 2.

4.2.5 Step 4: isolate vegetation management category

Generally, the Act regulates with varying levels of strictness, and this corresponds to management categories (Queensland Government 2018a). There are four other management categories classified under the Act (A,B,C,X). The most strictly protected vegetation category is Category A where clearing is prohibited. The least strict vegetation category is Category X which does not have enforceable guidelines around clearing. The remaining two categories under management are Category B (remnant vegetation) and C/R (high-value regrowth vegetation) (**Table 4-1**). To understand the implications for previously uncleared vegetation that is allowed to be cleared in the future, I considered clearing guidelines for remnant vegetation (Category B). Because remnant vegetation provides critical biodiversity habitat compared to non-remnant vegetation

(Lindenmayer et al. 2012, Watson et al. 2018) and because this category is the most exposed to guidelines, it was the most salient for analysis.

Table 4-1: Legislative definitions of Vegetation management categories as described under the Vegetation Management Act, 1999.

Vegetation Category	Definition
Category A	other than a Category B area, Category C area, Category R area or Category X area, shown on the regulated vegetation management map a. a declared area b. an offset area c. an exchange area **<u>or</u>** has been unlawfully cleared **<u>or</u>** is, or has been, subject to— i. a restoration notice ii. an enforcement notice under the Planning Act
Category B (Remnant)	other than a Category A area, Category C area, Category R area or Category X area, shown on the regulated vegetation management map as a Category B area that— a. contains remnant vegetation b. is a Land Act tenure to be converted under the Land Act 1994 to another form of tenure; and contains— i. an endangered RE ii. an of concern RE iii. a least concern RE
Category C	other than a Category A area, Category B area, Category R area, or Category X area, shown on the regulated vegetation management map as a Category C area that—contains high-value regrowth vegetation the chief executive decides to show on the regulated vegetation management map as a Category C area
Category R (regrowth-only applies post-2013)	other than Category A area, Category B area, Category C area or Category X area shown on the regulated vegetation management map as a Category R area that is a regrowth watercourse area
Category X	other than a Category A area, Category B area, Category C area or Category R area, shown on the regulated vegetation management map as a Category X area

4.2.6 Identify spatial features which constrain clearing

The guidelines describe where clearing may occur without triggering an environmental impact assessment. These spatial features relate to the landscape and include such things as slope, watercourses and wetlands, tenure, soil or essential habitat. In this step, I identified all spatial features which constrain clearing on remnant vegetation. The methods for spatial analysis including the spatial datasets for each attribute are listed and described in Appendix 4.

In addition to the criteria detailed in the clearing guidelines, I accounted for key federal legislation (the *Environmental Protection of Biodiversity Act, 1999; EPBC Act*), which states that clearing of vegetation cannot occur in areas occupied by a National Heritage place or World Heritage place; the catchment of a declared RAMSAR wetland or habitat for species listed under the EPBC Act. Furthermore, clearing in State Forests, National Parks, and other protected areas as defined by the *Forestry Act 1959* or the *Nature Conservation Act 1992* is not permissible and such areas were removed from all spatial layers relevant to this analysis. Data were available for World Heritage Areas, RAMSAR Wetlands, National Heritage Places, and State Forests and other protected areas, but not for threatened species distributions.

4.2.7 Comparative evaluation

I compared policy scenarios to 1. identify key policy changes to spatial features which changed how exposed certain areas are to clearing, 2. a statement to interpret the overall impact of the change and 3. describe the spatial effects in terms of an increased or decreased amount of assessable vegetation. To calculate a potential change in the amount of assessable vegetation, I applied the clearing guideline restrictions to Category B vegetation in ArcMap 10.7 (ESRI 2014). For example, if a clearing guideline states that clearing cannot occur within 200m of a major watercourse, then I created a 200m buffer around major watercourses and erased the buffered area from the Category B spatial layer. I restricted the spatial analysis to the *strict* and *relaxed* scenarios as these provided modern unlikely and likely scenarios for assessable vegetation. Based on the spatial analysis I summarized the total area available for clearing under each scenario by calculating the remaining area in ArcMap.

Here, I summarise the implications of these policies, but I did not create area estimates of the *modern* scenario. Unfortunately, the 2018 amendments to the Act meant that a spatial evaluation would have put me beyond the constraints required for timely PhD submission. I am working on creating these area estimates to publish this chapter as a paper, but, given that the *modern* scenario guidelines reverted many of the 2013 changes, I present estimates using this scenario. Specifically, the *modern* scenario omitted "thinning" as a relevant land clearing purpose. Removing the areas which can be cleared for thinning in the *strict* scenario from modern scenario estimates provides reasonable estimates of non-assessable vegetation. The only other significant change in the *strict* vs *modern* scenarios is the slight reduction in watercourse and wetland buffer areas.

4.3 Results

I present the results as 1) the key guideline changes and their implications; 2) the total amount of assessable vegetation in the *strict* and *relaxed* scenario. For more information concerning how spatial features compare per clearing purpose, schematic comparative summaries are presented in Appendix 4, **Figures A4-1- A4-5.**

4.3.1 Key policy changes

The *relaxed* guidelines differed from *strict* guidelines in five main ways resulting in a net increase of 1.8 million ha (2%) of deregulated remnant vegetation. The most significant changes were the re-introduction of broad-scale clearing. However, if a proponent was going to clear their land for agriculture or grazing, they were permitted to clear up to 5 ha per property without requiring an environmental impact assessment (Government. 2013a) (**Table 4-2**). This means that while 9.8 million ha (7%) of remnant vegetation occurs on highly arable soils (Department of Agriculture and Fisheries 2014) and could be cleared for this purpose, the extent of clearing per property without oversite is likely to be small. The second policy change reduced buffer zones from 200m to 100m around wetlands and watercourses. This change is applied to all clearing purposes (*ie* agriculture and grazing, extractive industry, encroachment, fodder harvesting and thinning). Consequently, approximately 2 million hectares (1.5%) of remnant vegetation of previously assessable vegetation became non-assessable with more potential clearing adjacent to waterways. The third change in guidelines removed at-risk and dense classifications of vegetation from spatial features of clearing guidelines. *Strict* guidelines classified regional ecosystems as "dense" (280,000 ha) or "at-risk" (4.8 million ha) **(Table 4-2)**. The relaxed guidelines did not mention these assessable categories (dense and at-risk). This means that more clearing could occur on these categories of vegetation. The fourth policy change introduction the concept of "self-assessable" clearing. Self-assessable means that a proponent of clearing does not have to provide evidence of clearing compliance or request permission to clear. This policy change assumes that proponents of clearing will read, understand and implement clearing following the regulations. The fifth significant change in guidelines removed the requirement for a proponent to demonstrate vegetation thickening had occurred. Previously, proponents were required to provide satellite imagery demonstrating thickening or encroachment in their application. The imagery or "proof" was vetted at the time of application, and, if thickening was not occurring, the application was not approved. Removing the need to demonstrate thickening and encroachment can result in an increased amount of vegetation clearing for this purpose, but not necessarily where it is needed **(Table 4-2).**

The *modern* guidelines differed from *relaxed* guidelines in five main ways (Table 4-3). The most significant and controversial changes was the removal of broad-scale to establish agricultural or grazing development. The second policy change was a reduction of buffer zones (no-clearing zones) around wetlands and watercourses (reduced from 100m to 20m). This policy change means that an increased amount of riparian vegetation can be cleared under the modern guidelines. The fourth policy change was the removal of *thinning* from the list of relevant clearing purposes. If a proponent wishes to clear their property of thickened vegetation, then they needed to apply for assessment under the *Planning Act 2016*. The guidelines for thinning and fodder harvesting received the most feedback (Butler et al. 2018) an extensive consultation and review process. In general, the feedback concluded that thinning vegetation is only consistent with the purposes of the Act where vegetation thickening is a threat to the ecological function and biodiversity of the local, regional ecosystem.

Table 4-2: Summary of the fundamental policy changes identified in a comparative analysis for the *strict* and *relaxed* scenario and then for the *relaxed* and *modern* scenarios.

Guideline change	Key spatial impacts	Interpretation	Clearing purpose effect
Fundamental changes between strict and relaxed scenarios			
Re-introduction of broad-scale clearing	Can clear remnant vegetation for broad-acre cropping	More least concern vegetation exposed under unregulated permits; of concern or endangered vegetation available with a clearing permit.	Agriculture and grazing
Changes to wetland and stream protection zones	Overall reduction of buffer zones in riparian areas, varying across Queensland	More vegetation available for clearing in riparian areas.	Agriculture and grazing, fodder harvesting, extractive industry, thinning and encroachment
Other classification changes (at-risk and dense vegetation)	Declassification of at-risk vegetation and dense vegetation	Vegetation in these categories is now available for clearing.	Agriculture and grazing, extractive industry, thinning
Removal of the requirements for vegetation clearing permits	No specific spatial impacts	Vegetation clearing can occur at a faster rate with the resultant reduced potential for regulation	Agriculture and grazing, fodder harvesting, extractive industry, thinning and encroachment
Removing the requirement to demonstrate thickening	Some listed regional ecosystems previously regulated can now be thinned. For all other regional ecosystems, no need to demonstrate thickening or encroachment with remote imagery	Vegetation clearing can potentially occur at a faster rate with the reduced potential for regulation. Vegetation clearing can potentially occur in areas where no thickening or encroachment is occurring.	Thinning
Removing regionally specific guidelines	Failure to consider the regionally specific environmental sensitivities	Vegetation clearing has no regionally specific context and therefore places no consideration on the impact per bioregion owing to its ecological dissimilarity.	Fodder harvesting, extractive industry, thinning and encroachment
Fundamental changes between relaxed and modern scenarios			
Removal of broad-scale clearing for establishing agricultural developments	Cannot clear remnant vegetation for establishing broad-acre cropping	Cannot clear remnant vegetation for establishing broad-acre cropping.	Cannot clear remnant vegetation for establishing broad-acre cropping
Changes to wetland and stream protection zones	Overall reduction of buffer zones in riparian areas, varying across Queensland	More vegetation available for clearing in riparian areas.	Agriculture and grazing, fodder harvesting, extractive industry, and encroachment
Introduction of riparian protection permits	No spatial impacts	Of the increased vegetation available to clear in riparian areas, there is greater scrutiny of clearing by departmental officers. This will likely result in higher compliance with the guidelines, and a decreased amount of vegetation cleared overall.	Agriculture and grazing, fodder harvesting, extractive industry, and encroachment

Guideline change	Key spatial impacts	Interpretation	Clearing purpose effect
Removal of thinning as a relevant clearing purpose	No spatial impacts	Vegetation clearing can occur at a faster rate with the resultant reduced potential for regulation	Thinning
Reinstating the need to demonstrate encroachment is occurring	No spatial impacts	Woody vegetation cleared because of the encroachment onto grassland regional ecosystems will be objectively assessed.	Encroachment

In both the *relaxed* and *strict* scenarios, the majority of (80-82%) remnant vegetation lacks spatial features that trigger assessable vegetation. Remnant vegetation which lacks these spatial characteristics is, in general, non-assessable if the total clearing in a single clearing event is less than a threshold stated in the guideline (generally between 2 and 5ha). In the *strict* scenario, there were 24,526,000 ha of assessable remnant vegetation. In the *relaxed* scenario, there were 82,750,000 ha of assessable remnant vegetation. About 15,322,000 ha of vegetation was overlapping across the assessable vegetation maps for strict and relaxed scenarios indicating that there is wide variation in both total extents as well as spatial configuration of regulated vegetation across the scenarios. Maps of these summaries are available in **Appendix 4, Figures A4-5, and A4-6**.

In the *relaxed* scenario, there was a net increase of 1.8 million ha (2%) of deregulated remnant vegetation primarily as a result of land made available for clearing for grazing and agricultural development through the re-introduction of broad-scale clearing. Broad-scale clearing was reintroduced to fulfill an election promise of doubling Queensland agricultural production by 2040 (Department of Agriculture 2014, 2013) to counter a global rise in demands for food and associated biofuel products (Miyake et al. 2012). Increased intensive land-use practices will likely reduce the quantity of remaining remnant vegetation resulting in increased erosion and soil loss. Doubling Queensland's agricultural production, however, will potentially place remaining remnant vegetation at increased risk of removal and further degradation. The second policy change reduced buffer zones (no-clearing zones) around wetlands and watercourses. Consequently, approximately 2 million hectares (1.5%) of remnant vegetation of previously assessable vegetation became non-assessable with more potential clearing adjacent to waterways. The re-introduction of broad-scale clearing permissions is likely to have adverse outcomes for biodiversity across the State. Indeed, the conversion of native habitat for land to grazing pasture and agricultural land has led to a rise in Queensland's clearing rates (Government. 2015a, DSITI 2017b) demonstrating the enormous effect this policy change had for vegetation in Queensland.

In the *strict* scenario, stream protection zones were based on biogeographic region but were reduced or eliminated. Removing and reducing stream protection zones made 2 million hectares of previously assessable vegetation nonassessable. After the changes, the State Government produced a land clearing report showed that 104,802 ha of vegetation was cleared in Great Barrier Reef Catchments (Government. 2015a) where increased sediment and nutrient run-off are known to be influencing marine health (De'ath et al. 2012). Given that vegetation around watercourses are crucial areas for preventing offshore impacts, governments should consider increasing these thresholds in future guidelines.

The *strict* scenario regulated clearing in dense regional ecosystems (280,000 ha) and at-risk regional ecosystems (4,879,000 ha). Clearing in these regions was prohibited for all purposes except for extractive industries. The changes to clearing guideline removed this regulation and exposed these dense and at-risk regional ecosystems areas to clearing. Large portions of at-risk vegetation communities were found in the Brigalow Belt and Mulga Lands where the majority of recent clearing has occurred (Government. 2015a). Reinstating at-risk and dense vegetation categories would constitute more robust protection of high-risk areas.

The purpose of making clearing self-assessable was to ease the regulatory burden for landholders to undergo routine maintenance on their properties. So, landholders no longer need to apply for permits to obtain permission to clear their properties (Taylor 2015). The proponents are no longer required to apply for and acquire a permit before clearing. This places the onus on the proponent to correctly interpret and apply the guidelines and leaves risks the misinterpretation, and therefore incorrect application of the guidelines. In the absence of formal applications and assessment processes, vegetation will likely be cleared, and adherence to the guidelines might diminish.

There was significantly more nonassessable vegetation that could be thinned or cleared for encroachment in the *strict* scenario (77,491,000 ha, **Table 4-3**). However, to clear thickened vegetation, a landholder must provide evidence (in the form of satellite imagery) that vegetation thickening or encroachment was happening. The *relaxed* scenario removed this requirement. Removing this requirement fails to account for thickening. Vegetation thickening can occur as a result of oscillations between El Niño and La Niña years where vegetation dieback during El Niño years is replaced by increased vegetative growth because of increased rainfall in La Niña years (Hughes 2003). It is, therefore, expected that vegetative thickening would occasionally occur. Although this selective clearing is not as transformative as broad-scale clearing, selectively disturbing an area to clear up encroaching or thickening vegetation does have potential negative impacts on biodiversity (França 2016) which should be considered. Removing the requirement to demonstrate vegetation thickening or encroachment allows for unnecessary or misinterpreted clearing (**Table 4-3**). Furthermore, owing to the highly dynamic Australian climate, thickening is often a critical phase of the natural, long term dynamics of vegetation as young trees and shrubs maximise rare opportunities to colonise and regenerate. If these events are classified as “thickening”, the, even selective, removal of vegetation will have negative impacts on biodiversity (Butler et al. 2018, Cardno 2015).

Table 4-3: Area (ha) of remnant vegetation available for clearing in the two scenarios and the total of combined vegetation available to clear. Numbers refer to guideline changes in Table 2 of the main text. ^All per cent remnant was calculated based on the 2015 extent of remnant vegetation for consistency across scenarios.

Purpose	Total available (ha) (*strict*)	%Remnant^	Total available (ha) (*relaxed*)	%Remnant^	Difference (*strict-relaxed*)	Per cent change
General	111,759,000	80%	113,612,000	82%	1,853,000	2%
Extractive industry	109,850,855	79%	113,612,000	82%	8,561,800	3%
Extractive industry (Key Resource Areas)	55,145	0%	0	0%	-55,145	0%
Encroachment	3,495,503	3%	4,912,200	4%	1,416,700	1%
Agriculture and grazing	0	0%	78,428,000	56%	78,428,000	56%
Agriculture (on arable soils)	0	0%	9,791,000	7%	9,791,000	7%
Fodder	6,205,000	4%	10,437,000	8%	4,232,000	4%
Thinning	112,420,000	81%	34,930,000	25%	-77,491,000	-56%
Available to clear	111,759,000	80%	113,612,000	82%	1,853,000	2%

4.4 Discussion

Queensland's Vegetation Management Act, 1999 was constituted to address growing concerns over the effects of broad-scale clearing of native vegetation, but also to encourage the ecologically sustainable land use which maintains regional biodiversity. The Act largely dictates the aegis under which land clearing can occur by regulating clearing in vegetation communities by assessable vegetation based on specific characteristics. Previous studies have shown that the Act has been ineffective in reducing land clearing (Simmons, Law, et al. 2018, Simmons, Wilson, et al. 2018). Since 2013, clearing rates have doubled in Queensland (Queensland Department of Environment and Science 2018), and, as of 2018, 224 of Queensland's 1,383 unique vegetation communities are listed as endangered, and 569 are listed as of-concern (Queensland Herbarium 2015) with that number expected to grow as more clearing occurs across the State. Failing to curtail land clearing raises concerns about the continued loss of habitat, and by extension, biodiversity. It would be useful for subsequent governments to be made aware of these potential consequences. There is potential need to redirect policy directives to cumulative evaluation so that the regulatory impacts can be understood, and policy interventions can be redirected towards species or communities that most urgently require an intervention. These interventions must then provide a quantifiable and clear line of sight regarding their benefit to the species ecological community.

If proposed land clearing is aligned with the distribution one of the ten spatial features described in **Figures 4-3** to **4-7** (*ie* essential habitat or slopes greater than 10%), then an environmental impact assessment is needed. If an environmental impact is not required, then clearing can go unmonitored and without ecological assessment. I found that the majority (80-82%) of vegetation in the *strict* and *relaxed* scenario lacked spatial features (such as essential habitat or proximity to wetlands) which made it assessable. In the *modern* scenario, it is clear that eliminating thinning and agriculture as relevant clearing purposes resulted in between 78,428,000 and 34,930,000 ha of remnant vegetation which could no longer be cleared. This means that the majority of the remnant (or previously uncleared vegetation) can be cleared in small portions without assessment, because small amounts of clearing may be necessary for the maintaining agricultural practices. A failure to assess the ecological consequences of clearing on non-assessable vegetation could result in severe declines in biodiversity across the State.

This study used comparative analysis to describe changes in clearing guidelines with regards to the biophysical and landscape features by which clearing is regulated. My analysis identifies several instances of policy change: 1) re-introduction of broad-acre cropping; 2) reduction in buffer zones around wetlands and watercourses; 3) deregulation of at-risk and dense vegetation; 4) introduction of 'self-assessable clearing'; 5) removal of the requirement to demonstrate vegetation thickening or encroachment; and 6) removing the regionally contextual guidelines and replacing them with State-wide regulations. In 2013, I identified changes in vegetation clearing principles in Queensland, and these changes may have consequences for biodiversity. A resurgence in vegetation clearing is directly linked to changes to the Act (Maron, Laurance, et al. 2015), and here I demonstrate that more vegetation was available for clearing for intensive land-use practices (agriculture, grazing and extractive industry) following the 2013 amendments. I found that the re-introduction of clearing for broad-scale agriculture has made over 9 million hectares of remnant vegetation likely to be cleared as these areas occur on soils suitable for agricultural or pastoral production. Additionally, alterations of the clearing guidelines (such as changes to stream protection zones) have increased the extent of vegetation available for clearing in critical riparian habitats. These changes have raised concerns among Queensland conservationists about the potential "weakening" of management legislation for the effective conservation of Queensland's biodiversity because of the consequences for woody remnant vegetation. From the perspective of landholder and land managers, however, the changes were a welcome reduction to a legislative burden which restricted their ability to efficiently use their land. Changes to the VMA as demonstrated here have clear consequences for both conservation groups and for land managers, and it is clear that extreme fluctuations to fit the priority of either stakeholder group may be met with an equally drastic shift under a new political regime. This study suggests there is a clear need to better understand the conflict between "conservation" and "agricultural" groups and for future policy development to consider harmonised outcomes that can be sustained in the long-term. The current conflict between both parties has resulted in a rapid and drastic shift in policy which may further entrench conflict and result in ineffective outcomes where both parties are concerned.

The majority of recent clearing in Queensland has been woody vegetation cleared to convert land to grazing pasture and forestry (Government. 2015a) with serious implications for biodiversity. For example, previous studies of the Lockyer Valley catchment in Southeast Queensland found that 41% of riparian vegetation was rated in poor or very poor ecological condition as a result of past clearing for agricultural purposes and subsequent exotic species invasion (Apan, Raine, and Paterson 2002). Such studies contextualise the long-term implications of broad-scale clearing and further demonstrate the need for careful consideration of the socio-ecological consequences of policy changes. The 2013 and 2018 amendments to the Act were significant because they introduced potential clearing to large areas of remnant vegetation. Both changes were introduced to fulfil an election promise. This article demonstrates how swiftly the Act can change with significant consequences for stakeholders and for remnant vegetation.

To simplify clearing guidelines for landholders and governments, clearing guidelines were aggregated by clearing purpose in the *relaxed* scenario and lost the bioregional considerations previously afforded. Such an aggregation means that clearing configurations might not address the specific ecological requirements of a bioregion. For example, remnant vegetation in bioregions where little remnant vegetation remains, such as the Southeast Queensland or the New England Tablelands, might require a smaller trigger threshold than a bioregion where there is a larger extent of intact remnant vegetation. Furthermore, not all ecosystems and species are ecologically equivalent. Clearing in highly speciose areas may have severe ecological outcomes that might not be realised for another 50-100 years (Verburg et al. 1999, Foley et al. 2005) and some species' persistence may tolerate clearing more than others.

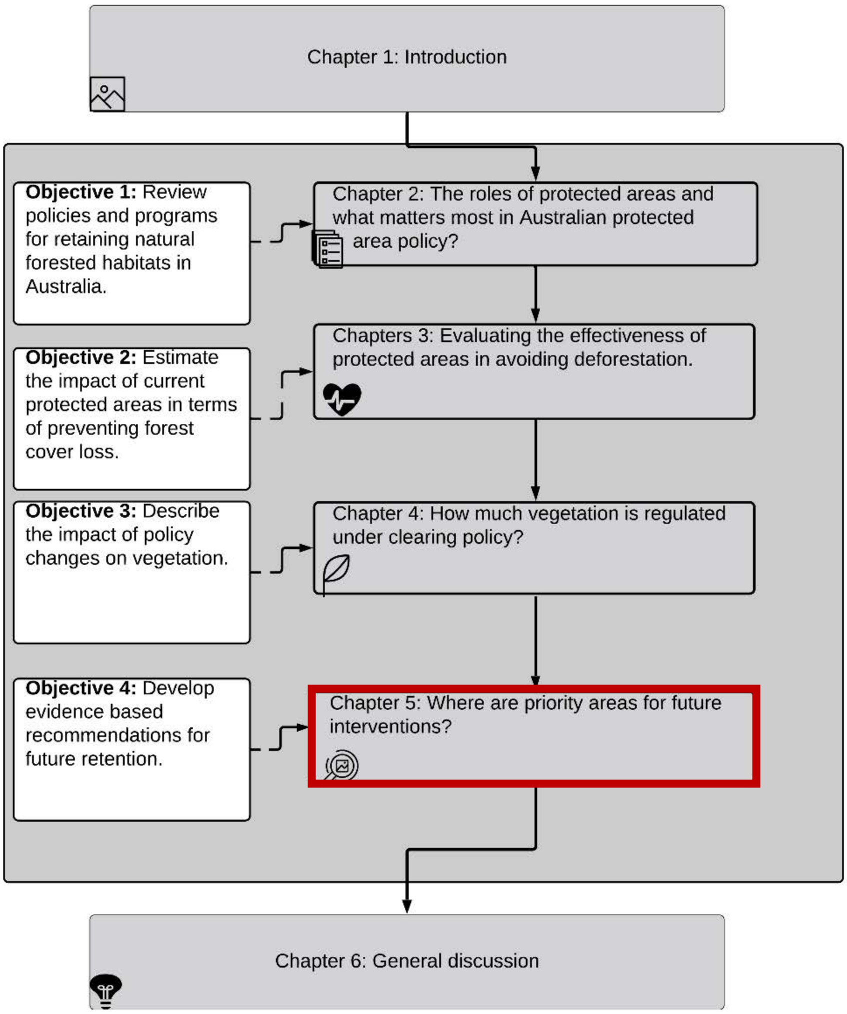
A well-known and unintended consequence of policy reform is an increase in vegetation clearing (Simmons, Law, et al. 2018, Whelan and Lyons 2005). Known as 'panic clearing,' it is believed that a surge in vegetation clearing before reform occurs when landholders view their future land rights with uncertainty (Lawes et al. 2015, Reside et al. 2017). Because panic clearing has been documented in Queensland before the initial ban of broad-scale clearing in 2004, it is clear that care must be taken in designing and implementing policy reform. As documented in this chapter, significant policy changes have occurred over the last eight years. Most recently, the *Vegetation Management (Reinstatement) and Other Legislation Amendment Bill* 2016 was introduced in March 2016 and passed in May 2018. Significantly, this bill removed the ability to obtain clearing permits for high-value agriculture and high-value irrigated agriculture. To avoid future panic clearing, governments must take clear and consistent approaches to vegetation management. The consequences of inconsistency is an increase in net forest loss (Australian Government 2012, Marcos-Martinez et al. 2018). Future policy development, if needed, require extensive consultation processes from both landholders and scientists to create a policy which minimising contention by marrying the expectations and values of all stakeholders.

In this study, I demonstrate a potential lack of security for most of the remnant vegetation owing to the fundamental lack of features that characterise assessable vegetation. Importantly, a lack of formal security means that non-assessable vegetation is highly vulnerable to changes in clearing policy. I note that the realised extent of vegetation clearing in Queensland, however, is much less than the extent available. A fundamental constraint to fully realised land clearing the explicit per property clearing thresholds described in the guidelines (*ie* up to 5 hectares) as well as the economic and practical constraints around clearing in remote regions (Evans et al. 2019).

Limitations and Assumptions

Clearing outside these guidelines is permissible with a development approval and following an environmental impact assessment. It was beyond the scope of this study to predict where potential development approvals would occur. I assumed that most land clearing in Queensland adheres to the guidelines. By assuming full compliance with the clearing guidelines, I am likely to underestimate potential clearing as larger development projects or those on assessable vegetation were not considered. Furthermore, any clearing activities that require offsets (or areas for which possible clearing must have exchange areas) were considered not available for clearing. Modelling offset purchases was not considered as a part of this study as purchases are highly variable and would present unreliable estimates. There are also exceptions listed in Schedule 21 of the Planning Act 2016 (formerly the Sustainable Planning Act, 2009).

Chapter 5. Assessing the threat of future clearing on vegetation communities in Queensland, Australia[4]



[4] This chapter is based on a journal article currently in prep

Abstract

Actionable decisions for conservation are fundamentally constrained by a lack of data to guide decision making. To remedy this for the state of Queensland, I modelled the probability of deforestation using a generalised estimating equation from a logistic regression model. I combined the modelled data with Queensland's vegetation community mapping to identify priority vegetation communities' areas for conservation. Assuming all high-probability areas are eventually cleared, I assessed the impact of this future deforestation against the legislative definitions for endangered, of concern or least concern communities. I identified which vegetation communities may become more vulnerable to extinction (*i.e.* become endangered). In doing so, I sought to address two critical knowledge gaps: i) of the bioregions included in this study region, where are areas with the highest probability of forest cover loss, ii) which communities may change their vulnerability status. I calculated a change in vulnerability status for three scenarios: unlikely, moderate, and likely. In the unlikely scenario, I identified 285 (0.3%) regional ecosystems overlap to some extent with high-probability areas, and 27 vegetation communities may change status at least once. In the moderate, 654 (42%) vegetation communities overlap to some extent, and 103 vegetation communities may change status. In the likely scenario, I found that 856 (55%) of Queensland's vegetation communities overlap to some extent with areas of high suitability for deforestation. I identified 192 vegetation communities that are likely change status (*i.e.* are currently least concern, but may become of concern). Of these, between 4-75 communities were currently least concern but may become endangered if clearing is not restricted. Least concern vegetation communities are not regulated under any environmental laws, and there are currently no legislative instruments for protecting communities under threat. I recommend that governments build on the results presented here to fill this diversifying current policy framework. This may include protecting species and communities which are under high levels of risk and undertake other management strategies where deforestation is not a significant threat.

5.1 Introduction

Globally, and as a consequence of the unprecedented expansion of built infrastructure and agriculture, approximately one-quarter of all species from red-list assessed groups are vulnerable to extinction (IPBES. 2019). Habitat loss by deforestation is considered a key threat to species by decreasing the size of the area available for species occupation and by fragmenting populations into small or isolated patches (Ceballos and Ehrlich 2002) (Tilman et al. 2017). To combat habitat loss, governments have developed programs and policies, including protected areas and vegetation regulation. The purpose of such measures is to ensure the persistence of species and communities. It is possible to bolster these programs with the addition of strategic and proactive measures. Measures that are strategic and proactive would identify communities or ecosystems with the highest risk of being lost. Without these measures, policies may be insufficient or at worst, ineffective in abating species and community loss.

Australia's highly distinctive biodiversity has suffered extraordinary rates of decline as humans increasingly modify natural environments (Evans et al. 2011, Carwardine et al. 2012). Although habitat loss is firmly attributed as the primary cause of current biodiversity decline (Woinarski, Burbidge, and Harrison 2015a), there is limited knowledge on the likelihood or probability of such loss across Australian landscapes. Such a critical knowledge gap fundamentally constricts decision-makers capacity to understand the effectiveness of a conservation action relative to inaction (Maron, Rhodes, and Gibbons 2013).

Predicting and planning for potential loss is fundamental for forest conservation and controlling deforestation. Modelling change in land cover (*ie* the probability that an area will be converted from natural to modified habitat) has attracted growing interest over the past decade. For predictive modelling to usefully inform governments and become integrated within an adaptive management framework, modelling approaches must be relatively accessible. Accessibility allows rapid, iterative policy production and updating to reflect the evolution of human landscapes and polices. The objectives of this study were to i) investigate where deforestation is most likely to occur based on an empirical spatial model and, ii) identify previously uncleared vegetation communities most susceptible to a change in biodiversity status as a result of deforestation pressure. To achieve this, I developed a predictive spatial model of deforestation for the Australian state of Queensland and then intersected this spatial model with the State's vegetation community mapping.

5.2 Methods

5.2.1 Study area

The study area constitutes nine of the thirteen bioregions within the state of Queensland, Australia. Bioregions are areas with similar climate, geology and biota (Thackway and Cresswell 1997) and are the primary reporting unit for biodiversity conservation in Queensland. I focused on the nine bioregions dominated by woody vegetation (**Figure 5-1**). I excluded four grassland-dominated bioregions (390,000 km^2 or 22.2% of land area in the State) because such habitats are incompatible with the modelling deforestation. The bioregions in the study area are diverse and consist of extensive areas of savannah, a mosaic of mangroves, pastures and remnant tropical forests. Approximately 19% of the land has been deforested (34,886,294 ha) since European colonisation (Queensland Department of Environment and Science 2018). Significant causes of deforestation are urbanisation, cattle ranching, agricultural production, and timber harvesting (Bradshaw 2012, Evans 2016, Seabrook, McAlpine, and Fensham 2006). Indeed, Queensland has experienced some of the world's highest deforestation rates for woody vegetation between 2015 and 2018 (Department of Science 1988-2016, Queensland Department of Environment and Science 2018) resulting in the classification of 45% of vegetation communities as "of-concern" or "endangered" (n=603, n=96).

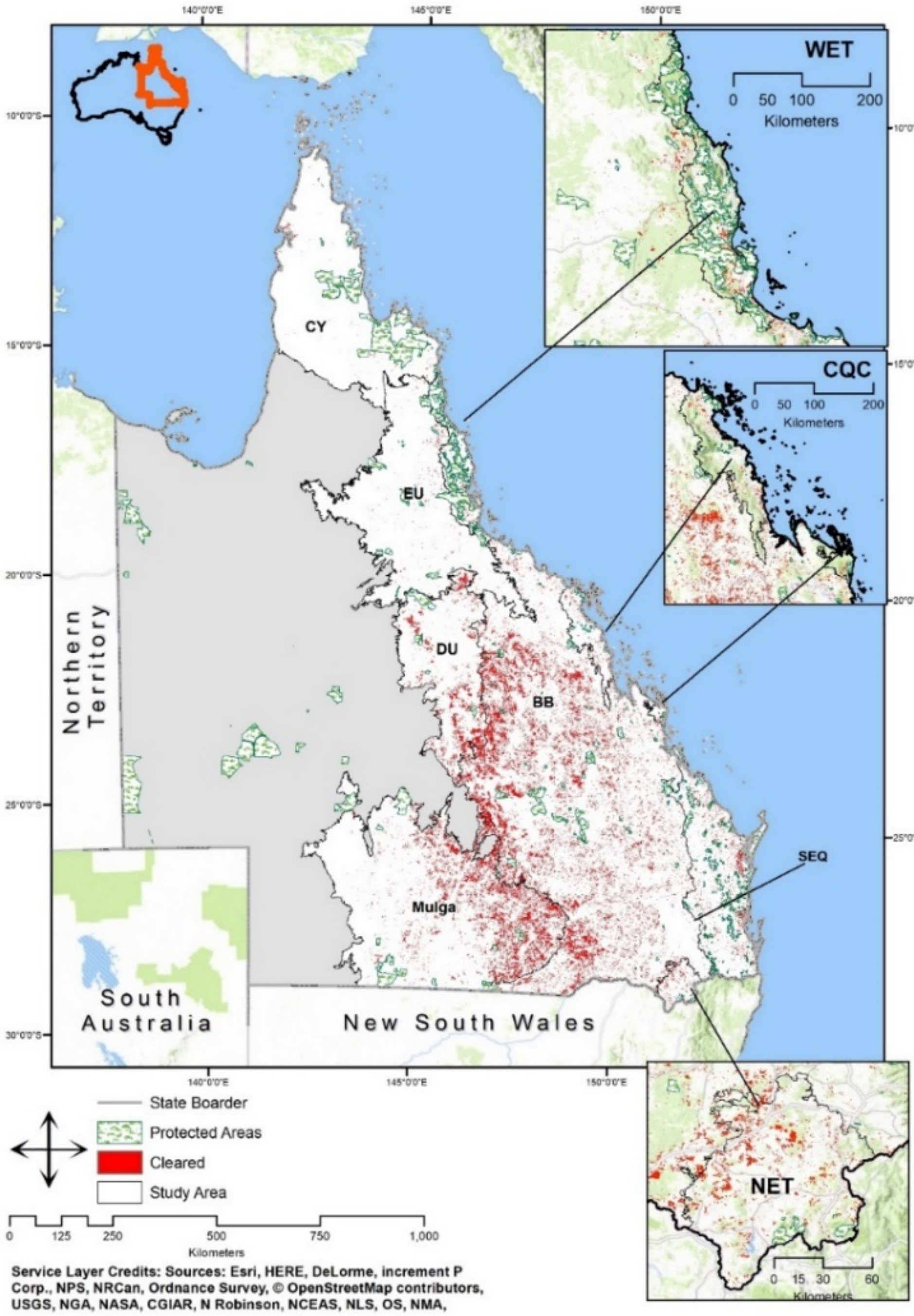


Figure 5-1: Map of the bioregions for this analysis. Areas that have been cleared in the last 30 years are shown in red. Protected areas as of 2019 are shown in green.

5.2.2 Data sources and pre-processing

Spatially explicit profiles of which consider the probability of deforestation can function as decision support tools. However, care must be taken in their design because the factors which influence deforestation vary globally and regionally (Simmons, Law, et al. 2018). Thus, the first modelling step is the proper identification of the proximate underlying causes of deforestation. From a comprehensive literature search, I concluded that the relevant characteristics in the Queensland context were: distance to markets, distance to major roads, distance to watercourses, grass biomass (cattle grazing capacity), rainfall, slope, and temperature (**Table 5-1**). To represent these characteristics, I obtained datasets from the Queensland Government's publicly available spatial data portal ("Q-spatial") (Queensland Government 2019) including layers representing the digital elevation model, grazing capacity, built-up areas, major watercourses, and state-controlled roads. I derived slope from a digital elevation model in ArcMap. To calculate the distance to built-up areas, distance to major watercourses, and distance to roads, I used the Euclidian distance tool in ArcMap (ESRI 2014). I created spatial layers for climatic variables (average annual temperature and average annual rainfall) from ANUCLIM using the Dismo package (Hijmans et al. 2017) in RStudio (RStudio Team 2015). I obtained a deforestation footprint (i.e. cleared/not cleared) (1988-2018) from the Queensland Government's "*State-wide land and trees study."* (SLATS) (Department of Science 1988-2016). Produced by the Queensland State Government under the "State-wide land and trees study" (SLATS), this data has a resolution of 30m*30m and was available from 1988-2018. (Department of Science 1988-2016). I removed areas attributed as "natural tree death" or "natural disaster damage" from further analysis. Thus, where clearing had occurred, a pixel was given a value of "1" indicating that a pixel contained woody vegetation before 1988, but was deforested at any point between 1988 and 2018. Values of "0" indicated no change in forest cover. Areas that were deforested before 1988 were also given a value of "0."

I divided each dataset into a 250 X 250 m grid cell based on the GCS GDA 1994, Zone 54 coordinate system. I collated the value at the central coordinate of each cell into a single dataset using the data.table package in RStudio (Dowle et al. 2019) and then separated by bioregion (n=9). I separated data by bioregion to account for each region's distinct ecological and biophysical characteristics. Using the same random sampling approach described in section 3.2.5 with sample sizes reported in **Table A3-3**.

Table 5-1: Description of each predictor, the logic behind its inclusion, the data source, year published, and data type. Datasets by the Queensland Department of Environment and Science, Department of Agriculture and Fisheries, or Department of Natural Resources and Mines were retrieved from http://qldspatial.information.qld.gov.au/catalogue/custom/index.page. I created Rainfall and Temperature data using ANUCLIM http://fennerschool.anu.edu.au/research/products/anuclim-vrsn-61.

Predictor variables	Rationale	Data source	Data year	Data type
Distance to built-up areas	There are higher costs associated with clearing lands that are further from current urban areas (Chomitz and Gray 1999)	Built-up areas: Department of Environment and Science	2014	Continuous
Distance to major roads	Roads facilitate access and are a known correlate to deforestation (Chomitz and Gray 1999).	State-controlled roads	2017	Continuous
Distance to watercourses	Increased access to surface water increases the likelihood of land development for agricultural or grazing purposes.	Watercourses: Department of Environment and Science	2014	Continuous
Grass biomass	Lands with higher pasture production are more likely to be cleared for grazing and less likely to be protected due to higher production value.	Agricultural land audit: Department of Agriculture and Fisheries	2014	Continuous
Rainfall	Land arability is a combination of climatic variables which may lead to competition between protection and production (Nori et al. 2013)	ANUCLIM	2017	Continuous
Slope	Flatland (low per cent slope) is easier to clear (Wilson et al. 2005)	Digital elevation model: Department of Natural Resources and Mines	2013	Continuous
Temperature	Land arability is a combination of climatic variables which may lead to competition between protection and production (Nori et al. 2013)	ANUCLIM	2017	Continuous

5.2.3 Modelling approach

The desired output of the model is a spatial layer representing the probability that a pixel will be cleared. I modelled potential deforestation using a generalised estimating equation for logistic regression in the Zelig package (Imai, King, and Lau 2009) in R v 3.6.1 and RStudio 1.2.1335 (RStudio Team 2015). I applied a generalised estimating equation to test the relationship between a dichotomous dependant variable (cleared/not cleared) and continuous independent variables (**Table 5-1**). Generalised estimating equations are highly appropriate for spatial data as they account for spatial autocorrelation (Zorn 2001) which can reduce model precision and predictive power (Mets, Armenteras, and Dávalos 2017). Generalised estimating equations are also demonstrably robust for non-Gaussian data and non-linear relationships between variables (Adeboye, Leung, and Wang 2017, Hubbard et al. 2010). In this case, a generalised estimating equation has the same form as a logistic regression which is commonly used in modelling deforestation probability (Aguiar, Câmara, and Escada 2007, Ludeke, Maggio, and Reid 1990). Furthermore, classic statistical tests, such as logistic regression have also been proven to perform as well as and sometimes better than more complicated models such as artificial neural networks (Mayfield et al. 2016).

To account for possible spatial autocorrelation, the model requires the specification of a working correlation structure. The working correlation structure can be independence, exchangeable, autoregressive, stationary, nonstationary, or unstructured (Chen and Lazar 2012). I chose an independence correlation structure because my outcome of interest is not time dependant (Gosho 2014, Wang 2014). A schematic representation for this modelling procedure is shown in **Figure 5-2.**

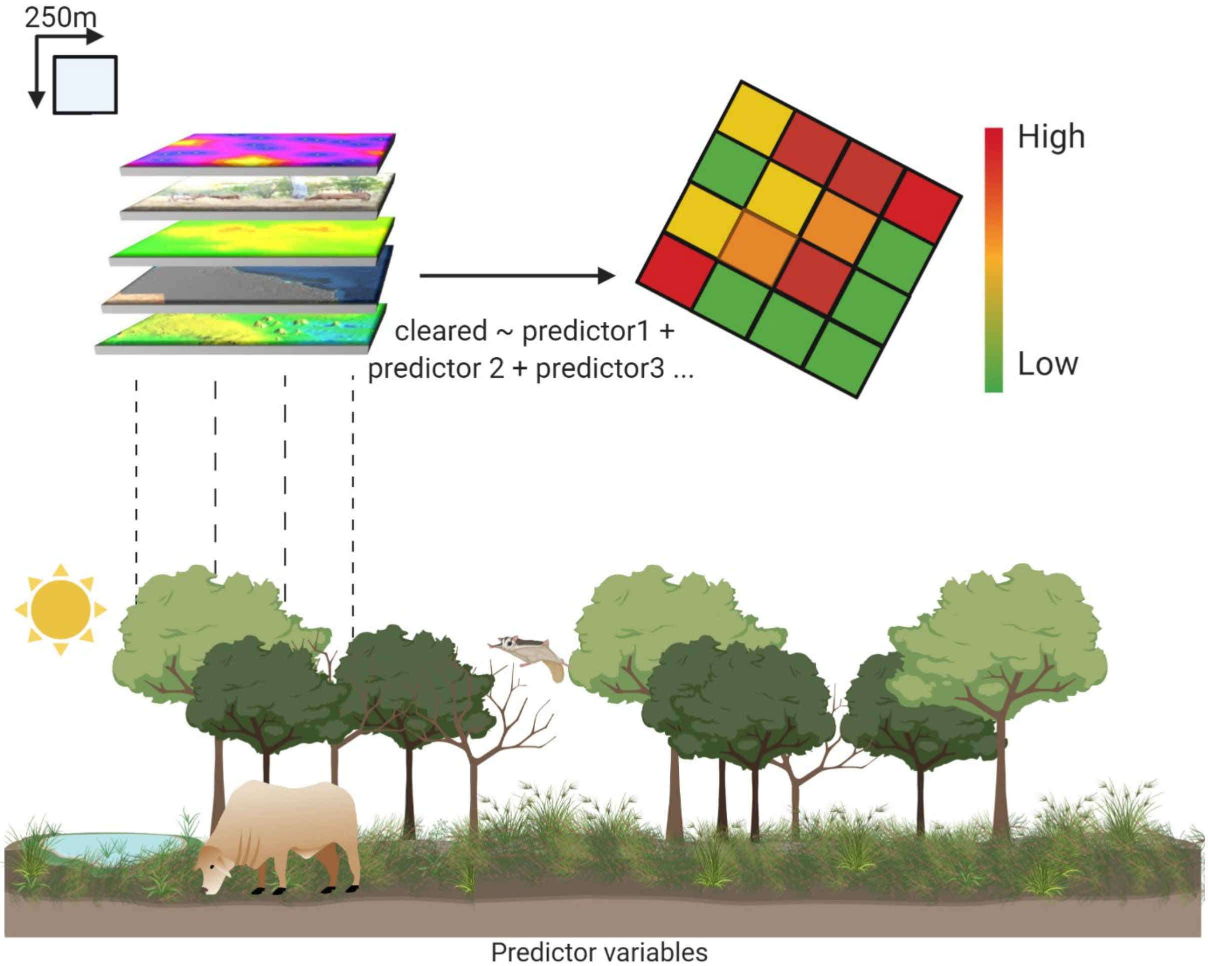


Figure 5-2: Schematic representation of the modelling procedure. Predictor variables listed in Table 1 were rasterised to a 250*250m resolution and then stacked into a single dataset per bioregion. I used a generalised estimating equation to predict deforestation probability.

5.2.4 Model calibration

To select the most parsimonious model, I performed a variable selection method which included excluding variables with an unacceptably high variance inflation factor (VIF >4) (Hair et al. 2013), highly correlated variables, and variables that were not significant predictors of deforestation (p>0.05). I created a predictive model for each bioregions model and ensured that all the variables included in the final model satisfied acceptable thresholds.

5.2.5 Diagnostics for model fit

I tested the model fit in two ways: using a Pearson's Chi-square goodness of it and calculating the area under the curve (AUC) (defined below). To calculate the chi-squared goodness of fit, I extracted 2,500 random samples of 100,000 observations of the predicted (modelled) and observed (cleared or not cleared) values. For each sample, I calculated the Pearson's chi-square test statistic. I report on the average of these samples and show boxplots and histograms of the imputed p-values in Appendix 5. Next, I plotted the receiving operating characteristic curves (ROC) using the pROC package (Robin et al. 2011) in Rstudio (RStudio Team 2015). In this accessible diagnostic, sensitivity (or the probability of predicting a true positive) is plotted against 1-specificity (or the probability of false-positive). Model performance is considered acceptable if the curve is quite steep, rising steeply with the Y-axis and then following the top border. The area under the (receiving operating characteristic) curve (AUC) is a statistical measure of how closely the model fits the desired curve. An AUC higher than 0.7 is considered acceptable, and a value of 1.0 is considered perfect (Mandrekar 2010).

5.2.6 Model confidence

To assess confidence in the predicted deforestation probability values from each bioregion's model, I calculated confidence intervals per pixel (or row within my datasets) using a nonparametric bootstrapping technique with the Boot package (Canty and Ripley 2019). Bootstrapping produces a frequency distribution by resampling the model's predicted values 500 times for 100,000 rows of data and then calculating the sample mean per resample (Burbrink and Pyron 2008). Using these imputed means, I then extracted the standard error. The 95% confidence limits were calculated by adding or subtracting the standard error of the bootstrapped mean to with mean of the predicted values and then multiplying by 1.96 (Carpenter and Bithell 2000). I summarise by reporting on the 95% intervals in this way:

$$(1)\ CI_m = Mean \pm (SE_{boot} * 1.96)$$

Where "*mean*" is the mean predicted deforestation probability values per bioregion and "SE_{boot}" is the standard error of the bootstrapped simulation.

5.2.7 Combining with vegetation community data

Once satisfied that each bioregion's model was well-calibrated, I combined the values for each bioregion into a single spatial dataset. I then isolated areas with the highest probability for deforestation, by reclassifying predicted values for the following three scenarios: i) unlikely: predicted probability of deforestation values above the mean (*ie* predicted values >7% and including outliers) for the whole study area were reclassified with a value of "1" and values below the mean as "0" **(likely)** ii) moderate: predicted values above in the upper quartile (*ie* predicted values >11% including outliers) for the whole study area were reclassified with a value of "1" and values below the mean as "0 " **(moderate)** and iii) likely: predicted values above the upper whisker (*ie* outliers only or predicted values >25%). for the whole study area were reclassified with a value of "1" and values below the mean as "0" **(unlikely).** This created three binary spatial layers with values of "1" denoting areas most likely to be cleared and "0" denoting areas less likely to be cleared. I then used the Raster package (Hijmans et al. 2015) to create spatial grids (250m*250m) of these binary classifications and then exported the raster to ArcMap 10.7 (ESRI 2014).

Queensland's vegetation communities are mapped into "regional ecosystems." which constitute a world-class vegetation community dataset and is a useful proxy for biodiversity. Regional ecosystems (Neldner et al. 2012) are mosaics of geology, landforms, dominant vegetation, and are mapped at a scale of 1:50,000 in the Wet Tropics bioregion and 1:100,000 across the rest of the State.

I used the most recent and comprehensive depiction of Queensland's natural communities: version 11.1, which included mapping of 1,542 regional ecosystems (Queensland Herbarium 2019). I used two regional ecosystem datasets: preclear and remnant. The first dataset is the expected distribution of a regional ecosystem in the absence of European settlement and deforestation. The second refers to the current extent of the regional ecosystem. Some polygons were mapped as "mosaics" where a maximum of five regional ecosystems could occur within a single polygon. I assumed that the area of any particular regional ecosystem is equal to the total polygon area multiplied by the per cent of that polygon attributed to that particular regional ecosystem. Finally, I calculated the total area of overlap of Queensland's vegetation community mapping (regional ecosystems; described below) by intersecting the regional ecosystem mapping with pixels classified as "1" (or probability of deforestation) for each of the three scenarios described above (DeCoster, Gallucci, and Iselin 2011). I also assumed that deforestation was uniform in areas where it overlapped with a possibility of deforestation.

A vegetation communities' threat status is legislatively related to the percent of vegetation remaining and to the amount of that system that existed prior to European settlement (**Table 5-2**). To calculate the amount of each regional ecosystem remaining if all areas were cleared, I used the simple formula below:

$$(2)\ \%remaining = \left(\frac{(\text{Area}_{pot} - Area_{pa}) - Area_{2019}}{Area_{preclear}}\right) * 100$$

Where the per cent remaining is the proportion of the regional ecosystem's pre-cleared ($\text{Area}_{\text{prelear}}$) extent if all potential areas (Area_{pot}) areas (excluding those currently under protection, Area_{pa}) are cleared from the current extent, Area_{2019}. In this context, high-probability was defined based on the three (likely, moderate, and unlikely case) scenarios described above.

5.2.8 Predicting a change in vegetation management status

The state of Queensland regulates its vegetation communities by assigning a status to each regional ecosystem which signifies its vulnerability to extinction (Government. 2015b). Among other things, this status is relative to the amount of the regional ecosystem remaining and included the following categories: least concern, of concern, and endangered (**Table 5-2)**. Status categories are used for planning and management activities under Queensland's *Environmental Protection Act 1994* and *Vegetation Management Act 1999.* I calculated the per cent of each regional ecosystem remaining and assessed the value by the biodiversity status definitions shown in **Table 5-2.** Biodiversity status has two major considerations: the total amount of a particular regional ecosystem remaining relative to its pre-European settlement (pre-clear) extent, and whether or not a particular regional ecosystem is naturally rare (*ie* has a pre-clear distribution of less than 10,000 ha). For example, a regional ecosystem is considered least concern if greater than 30% of its pre-clear extent remains. If its remaining extent falls below 30% and the extent is greater than 10,000 ha, then it is classified as of concern.

For each scenario (**likely, moderate** and **unlikely**) I calculated the total area of overlap between each regional ecosystem and areas with a pixel value of "1" (i.e. possibility of deforestation). I assumed that any pixels with a value of "1" will be cleared at some point in the future and noted any regional ecosystems that would experience one or more possible status changes. An example of one status change would be transferring from a least concern status to an of concern status. An example of two status changes would be moving from a least concern status to an endangered status. In summary, the steps associated with this analysis are:

1) Calculate the total area of future deforestation based on the extent to which each vegetation community overlaps with the probability of deforestation scenarios described above;

2) Calculate the area likely to remain intact based on each of the scenarios and subtract that area from the current extent. The remaining area from this subtraction is divided by the total area before European settlement (pre-clearing).
3) The per cent that is derived from step 2 is then associated with the appropriate vegetation community status (*e.g.* endangered).
4) All status changes are recorded including instances where a vegetation community will make more than one change.

For example, regional ecosystem 11.7.7 is described as a mixture of Eucalyptus and Corymbia woodlands on Cainozoic lateritic duricrust and is currently considered least concern. It has an estimated pre-European extent of 203,764 ha, but, as of 2018, had been reduced to 174,903 ha. A further 169,931 ha of this regional ecosystem occurs on areas which may be cleared according to the unlikely scenario. Furthermore, regional ecosystem 11.7.7 does not occur in protected areas. If all high-probability areas in this scenario are assumed to be fully cleared, only 4,971 ha (2% of its pre-European extent) would remain. If regional ecosystem 11.7.7 is reduced to 2% of its pre-European extent, then it would be classified as an endangered regional ecosystem where, previously, it was considered least concern. Such status changes have significant implications in terms of future strategic planning.

Table 5-2: Vegetation Management Status Categories as per Queensland's Vegetation Management Act 1999.

Remnant Vegetation Management Status	*Definition*
Endangered	Remnant vegetation in regional ecosystem with: 1. less than 10% of their pre-clearing extents remaining, or 2. 10–30% of their pre-clearing extents remaining and the remnant vegetation covering less than 10,000ha, or 3. less than 10% of their pre-clearing extents remaining unaffected by severe degradation* and biodiversity loss, or 4. 10–30% of their pre-clearing extents remaining unaffected by severe degradation and biodiversity loss and the remnant vegetation covering less than 10,000ha, or 5. classification as rare** or subject to a threatening process***.
Of-Concern	Remnant vegetation in regional ecosystems with: 1. 10–30% of the estimated mapped extent before European settlement remaining; or 2. more than 30% of the estimated mapped extent before European settlement remaining and the remnant extent less than 10,000 ha, or 3. 10–30% of the estimated mapped extent before European settlement remaining unaffected by moderate degradation and biodiversity loss.
Least Concern	Remnant vegetation in regional ecosystems with: 1. more than 30% of their pre-clearing extents remaining, and remnant area greater than 10,000 ha, or degradation criteria listed above for 'endangered' or 'of concern' are not met.

* The Vegetation Management Act, 1999 defines severe degradation as a substantial loss of floral or faunal diversity which is unlikely to recover within the next 50 years, even if threatening processes are removed; or substantial impacts on the soil surface, with loss of a-horizon surface, expression of salinity, soil compaction, loss of organic matter, or sheet erosion.

** A regional ecosystem is considered rare under the Vegetation Management Act, 1999 if it is predicted to have had an extent of 1,000 ha before European settlement.
*** A process is considered threatening if it is reducing or will reduce the biodiversity or ecological integrity of a regional ecosystem.

5.3 Results

5.3.1 Model fit and confidence

I tested for model fit using chi-squared tests and ROC and AUC values. I then calculated the confidence intervals and mapped them per pixel (Appendix 5; **Figures A5-22 to A5-30**). Based on the mean of the chi-square simulations, I concluded that the model accurately predicts where deforestation would occur because it successfully predicted cleared pixels. ($p>0.05$) (**Table 5-3**).
Furthermore, the AUC values ranged from 0.623 (New England Tablelands) to 0.836 (Wet Tropics) indicating acceptable model fit for all bioregions except the New England Tablelands (see ROC curves in Appendix 5). I found that the confidence intervals obtained by bootstrapping had a negligible effect on the mean predictions ($8.57*10^{-6}$ to $1.96*10^{-4}$). Considering these three tests, I conclude that my models are well-fitted to the data and that the provided predictions are reliable (Alsadik 2019, Ling, Huang, and Zhang 2003).

Table 5-3: A description of the variables included in the final model ($p<0.05$) for each bioregion. "Built" refers to Euclidean distance to built-up areas, "graze" refers to grass biomass, "rain" refers to average annual rainfall, "roads" refers to Euclidean distance to State-controlled roads, "slope" refers to slope in per cent rise, "temp" refers to yearly average temperature, "wc" refers to Euclidean distance to major watercourses. The third column shows the mean (M) of simulated Pearson's Chi-Squared goodness-of-fit values. Chi-square tests whether or not the observed data are consistent with the values imputed from the models (Alsadik 2019). ^ indicates that there is no significant difference between the predicted and observed deforestation data and the models have performed well. The final column is the mean (M) confidence interval (upper and lower 95% of values) for each bioregion (see methods: model confidence).

Bioregion	List of covariates	M.Chi-square	M.df	M.pvalue	M. Confidence intervals
Brigalow Belt	Built, rain, roads, slope, temp, wc	97855	97853	0.4980^	$0.103 \pm 5.27*10^{-5}$
Cape York	Graze, rain, slope, temp wc	96995	96994	0.4919^	$3.40*10^{-3} \pm 7.35*10^{-6}$
Central Queensland Coast	Graze, rain, roads, slope, temp, wc	78567	78573	0.5083^	$3.697*10^{--2} \pm 1.53*10^{-4}$
Desert Uplands	Graze, rain, roads, slope, temp, wc	95021	95017	0.4961^	$0.0910 \pm 1.96*10^{-4}$
Einasleigh Uplands	Built, graze, rain, roads, slope, temp, wc	98645	98646	0.4993^	$1.016*10^{--2} \pm 8.57*10^{-6}$
Mulga Lands	Graze, rain, slope, temp, wc	98176	98174	0.4976^	$0.0990 \pm 1.35*10^{-4}$
New England Tablelands	Built, roads, slope, temp, wc	66508	66498	0.4918^	$0.0714 \pm 1.71*10^{-4}$
Southeast Queensland	Built, graze, roads, rain, slope, temp, wc	94595	94586	0.4921^	$0.0512 \pm 7.85*10^{-5}$
Wet Tropics	Built, graze, rain, roads, slope, temp, wc	83461	83466	0.5006^	$0.0224 \pm 1.21*10^{-4}$

Across the study area, the probability of deforestation (predicted values) ranged from 0 to 97.7%. The estimated probability of deforestation in each bioregion was highly variable across regions. Higher probabilities were observed in the Brigalow Belt and Mulga Lands compared to other bioregions (97% and 90% respectively). Lower maximum probabilities were observed in the Cape York (0.016%), Central Queensland Coast (0.025%), and Wet Tropics (0.020%) bioregions, and confidence bands increased or decreased these maximum estimates by 0.02% (**Figure 5-3)**.

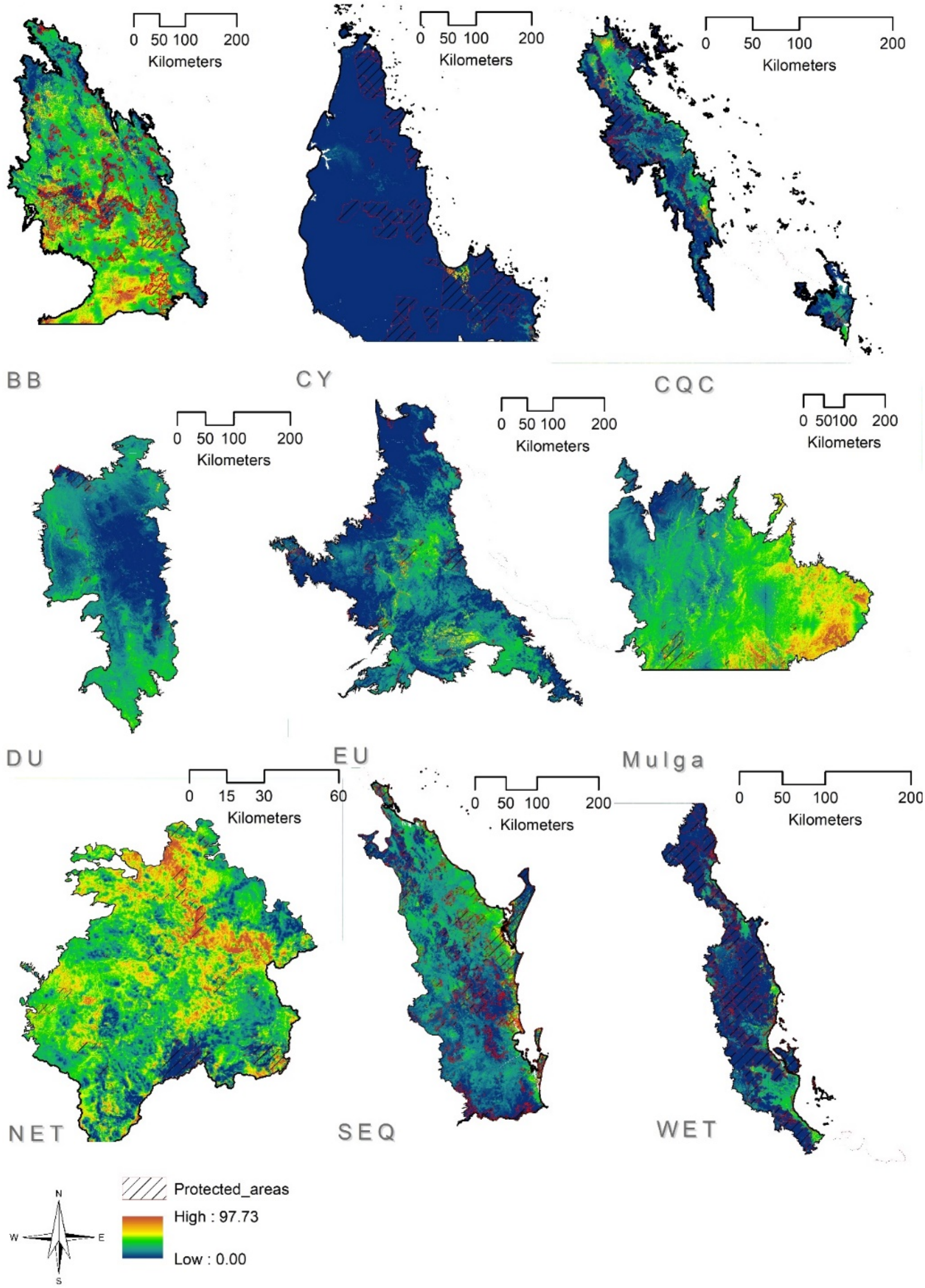


Figure 5-3: Map of the likelihood that a pixel will be cleared given the relevant biophysical characteristics of the pixel. The predicted values for each bioregion are shown in a combined raster format "predicted values."

5.3.2 Probable deforestation and impacted regional ecosystems

There was significant variation in the total area of overlap between the likelihood of deforestation and regional ecosystems across the three reclassification scenarios (*i.e.* **unlikely, moderate,** and **likely**). This suggests that, while it is common to reclassify the top 50% of values as "high" and the bottom as "low," such an exercise may be misleading and care must be taken when reclassifying continuous data into categorical bins.

5.3.3 Probable deforestation and impacted regional ecosystems: Unlikely

Under the unlikely scenario, I estimated 19,911,658 ha or approximately 20% of the study area in Queensland **(Figure 5-4)** has at least a 7% probability of being cleared (**unlikely**). The majority of areas (87%) with a possibility of clearing occur in the Mulga Lands (44% of the bioregion, 8,944,000 ha) and Brigalow Belt (43% of the bioregion, 8,307,000 ha) bioregions. The smallest areas predicted are in the Cape York and Einasleigh Uplands bioregions. Regional ecosystem from the Mitchell Grass Downs and Channel Country bioregions (n = 55, 2,9540 ha) encroached on adjacent bioregions (Einasleigh Uplands and Desert Uplands) and overlapped with areas with potential for deforestation. For this reason, these bioregions appear in **(Figure 5-4).**

5.3.4 Probable deforestation and impacted regional ecosystems: Moderate

I estimated 9,124,694 ha or 9.3% of the study area has at least an 11% probability of being cleared (**moderate**) **(Figure 5-4)**. Again, many of these areas are in the Brigalow Belt (43%, 3,905,097 ha) and Mulga Lands (44% 3,995,525 ha). The smallest areas observed are in the Cape York bioregion (280 ha). Some regional ecosystems from the Channel Country and Mitchell Grass Downs were observed in this dataset because they had encroached on adjacent bioregions and overlapped in areas with a moderate likelihood for deforestation (n=40, 12,582 ha).

5.3.5 Probable deforestation and impacted regional ecosystems: Likely

I estimated that 336,323 ha or 0.3% of the study area in Queensland has at least a 25% probability of being cleared (lower estimate, **likely**) **(Figure 5-4)**. Many of these areas are in the Brigalow Belt (122,920 ha, 36.5%), the Desert Uplands (119,933 ha, 35.6%), and the Mulga Lands (88,744 ha, 26%). The smallest areas were in the New England Tablelands (168 ha, <0.1%) and Southeast Queensland (24 ha, <0.1%). There were no areas in the Cape York, Central Queensland Coast, or Wet Tropics bioregions with a probability of deforestation greater than 25%.

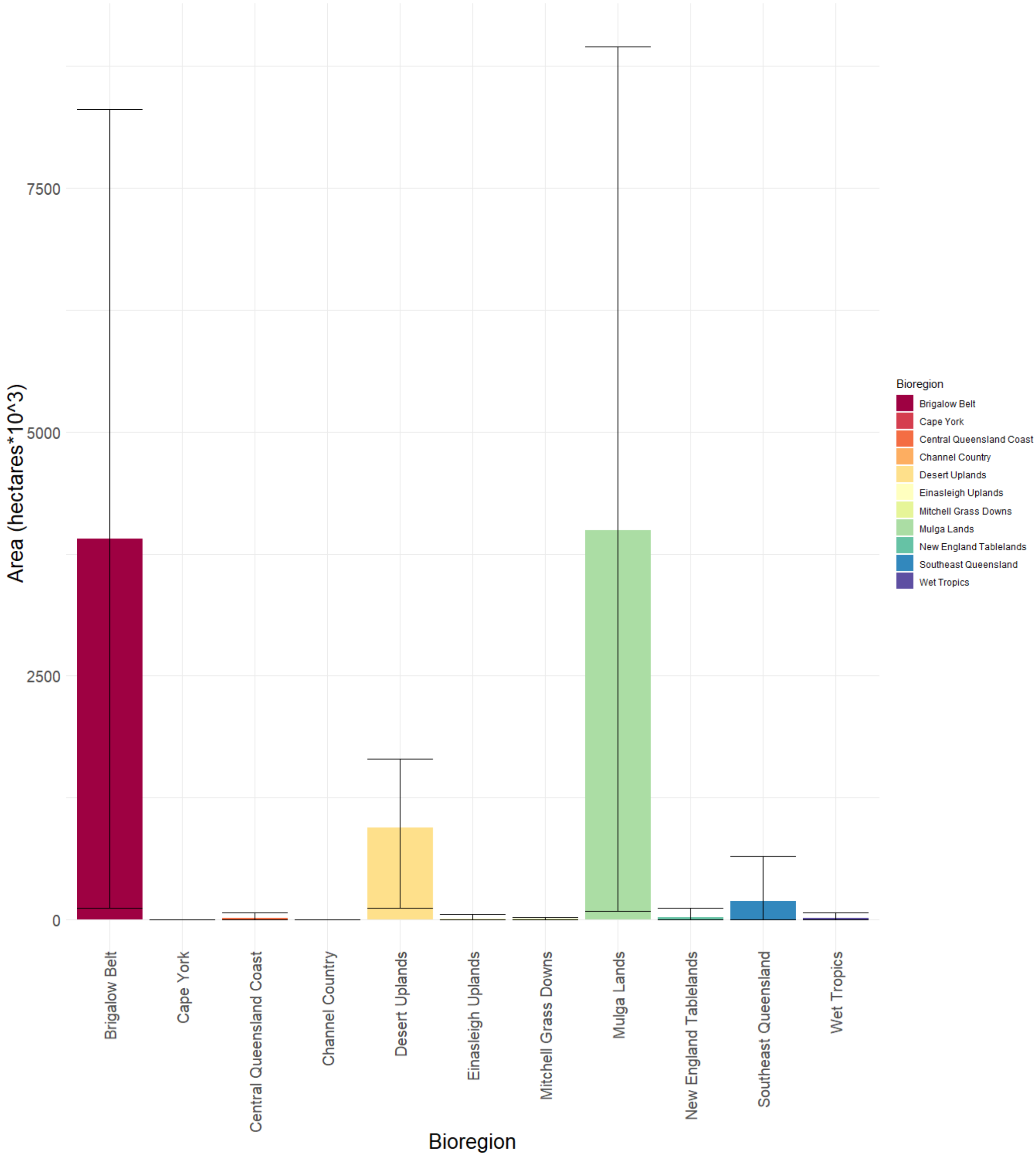


Figure 5-4: Area with a possibility for deforestation under three reclassification scenarios: unlikely (upper whisker) moderate (coloured bars) and lower-estimate (likely). In this context, probability values above the mean were reclassified as "1" (unlikely), probability values above the upper quartile were reclassified as "1" (moderate) and probability values above the upper whisker (*i.e.* outliers) were reclassified as "1" (likely). The three classification strategies demonstrate high variability depending on which approach is taken.

5.3.6 Impact of predicted deforestation on regional ecosystems: the unlikely scenario

Over half of the currently mapped regional ecosystems (55%, n=856) overlap to some extent with the possibility of deforestation under the likely scenario. However, the extent of overlap in terms of the total current area of a particular regional ecosystem was highly variable with a minimum of 0% to a maximum of 100% (n=20). The average area of overlap was 27%. The number of regional ecosystems with an extent of overlap of less than 1% of their total area was 283. The amount of overlap has implications for each particular regional ecosystem's vegetation management status. I found that 194 regional ecosystems overlap to such an extent that they are likely to change the vegetation management status at least once. Most of these regional ecosystems are in the Brigalow Belt (n=75) and Mulga Lands (n=50) and the fewest came from the New England Tablelands (n=5) and the Central Queensland Coast (n=8). I found that 75 regional ecosystems are likely to change from a least concern status to endangered status. For these regional ecosystems, there are two potential status changes: least concern to of concern, and then of concern to endangered. Furthermore, I found that 49 regional ecosystems are likely to change from a least concern status to an of concern status. I also found an additional 68 regional ecosystems that were likely to change from an of concern status to endangered status **(Table 5-4)**.

5.3.7 Impact of overlap on regional ecosystems: moderate scenario

Nearly half of Queensland's regional ecosystems overlap with areas of moderate probability for deforestation (42%, n =653), however, the total extent of this overlap was highly variable ($9.29*10^{-9}$% to 99.72% with an average overlap of 7.3%). There were 103 regional ecosystems where less than 1% of their current extent overlapped in areas with a moderate potential for clearing. In this scenario, 89 regional ecosystems overlapped to such an extent that they are likely to change the vegetation management status at least once. The majority of these regional ecosystems were from the Brigalow Belt (n = 30) and Mulga Lands (n=29). The fewest regional ecosystems that are likely to change status was observed in the New England Tablelands (n=1). I found that 27 regional ecosystems could change by two levels from least concern to endangered status. I found a further 21 regional ecosystems which can change from an of concern to endangered status, and 41 regional ecosystems which may migrate from least concern to an of concern status. **(Table 5-4)**.

5.3.8 Impact of overlap on regional ecosystems: likely scenario

I identified 284 regional ecosystems that overlap with areas that have the potential for deforestation (18%) according to the likely scenario. This range of overlap, however, was highly variable, ranging from 0% to 26.75% with an average overlap of 1.4%. Of these, there were 210 regional ecosystems where less than 1% of their current extent overlapped with potential deforestation areas. In this scenario, 27 regional ecosystems overlapped to such an extent that they are likely to change the vegetation management status at least once. Of these, the majority were from the Southeast Queensland bioregion (n=11, 36%) and Mulga Lands bioregions (n=7, 23%). The fewest regional ecosystems were observed in Cape York (n=1) and Einasleigh Uplands (n=1). I found that two regional ecosystems could change from least concern to endangered status, both of which are in Southeast Queensland. A further eight regional ecosystems could change from an of concern to endangered status, and 15 regional ecosystems could change from least concern to an of concern status. **(Table 5-4)**.

Table 5-4: Summary table of the number of regional ecosystems effected in each bioregion per scenario. L_1change is the number of regional ecosystems per bioregion that will change status at least once in the likely scenario. L_2change is the number of regional ecosystems that will change status twice in the likely scenario. Mod_num is the number of regional ecosystems effected in the moderate scenario. Mod_1change is the number of regional ecosystems per bioregion that will change status at least once in the moderate scenario. Mod_2change is the number of regional ecosystems that will change status twice in the moderate scenario. WC_num is the number of regional ecosystems affected in the likely scenario. UN_num is the number of regional ecosystems effected in the unlikely scenario UN _1change is the number of regional ecosystems per bioregion that will change status at least once in the unlikely scenario. UN_2change is the number of regional ecosystems that will change status twice in the unlikely scenario.

Bioregion	L_num	L_1change	L_2_change	Mod_num	Mod_1change	Mod_2change	UN_num	UN_1change	UN_2change
Brigalow Belt	114	2	-	157	30	6	166	74	27
Cape York	1	1	-	20	-	-	66	1	-
Central Queensland Coast	8	3	-	41	2	-	65	7	-
Channel Country	-	-	-	11	-	-	25	1	-
Desert Uplands	69	-	-	74	8	-	75	15	3
Gulf Plains	-	-	-	-	-	-	-	2	-
Einasleigh Uplands	19	1	-	51	-	-	78	-	-
Mitchell Grass Downs	17	0	-	29	-	-	29	1	-
Mulga Lands	40	7	-	64	29	9	64	45	31
New England Tablelands	5	-	-	13	1	-	22	4	2
Northwest Highlands	1	1	-	-	-	-	-	-	-
Southeast Queensland	12	12	2	126	17	4	152	12	9

5.4 Discussion

The objectives of this study were to 1) investigate where deforestation may occur based on an empirical spatial model and, 2) identify previously uncleared vegetation communities most susceptible to a change biodiversity status as a result of deforestation pressure. Doing so enables us to guide proactive protection of vegetation at risk. To this end, I modelled changes in vegetation management status category for regional ecosystems based on three scenarios of deforestation. I found that some bioregions are particularly at risk, and between 12 and 152 regional ecosystems may change threat status due to future risk of deforestation under the likely and unlikely scenarios, respectively.

Predictive modelling functions as an essential decision-support tool that can be used to assist conservation and management policy and practices (Veldkamp and Lambin 2001b, Sutherland and Freckleton 2012). Adding to current knowledge about the status of biodiversity in Queensland, I predicted the probability that currently forested pixels could become deforested and then used this to estimate the risk to the status of regional ecosystems from deforestation. The modelled predictions were effective in representing potential deforestation across Queensland. As expected, I identified variation in both the predictors of deforestation and the maximum potential for deforestation between regions.

Candidate predictor variables were systematically excluded from the bioregions final model using variable selection methods; however, some key predictors were common to the most parsimonious model across all bioregions. Namely: slope, average annual temperature and distance to major watercourses (**Table 5-3**). These variables may be considered proxies of deforestation drivers as they directly relate to accessibility and probability for development (Department of Climate Change and Energy Efficiency. 2017, Jackson 2016). While there is extensive literature supporting the influence of roads on deforestation rates, this is not always the case. In this context, distance to roads was a significant predictor variable in six of the nine bioregions. Similarly, de las Heras *et. al.* (2012) found that the influence of road networks on deforestation will become saturated and no longer useful in predicting cleared areas, but that topographical features are more consistently limiting than roads. Indeed, as slope had statistical significance in all bioregions, my findings support this concept.

The maximum probability of deforestation varied considerably across the regions, but was relatively low across the State. The thresholds considered in the model were (greater than 7%, unlikely, greater than 11%, moderately likely, and greater than 25%, likely). This suggests that deforestation probably over a 30-year period is unlikely to impact the majority of vegetation communities in Queensland in the next few decades, and may indicate that deforestation is a dwindling threat in Queensland. Further studies are needed to test this concept, however, if that is the case, then conservation efforts may need to focus on restoration activities to restore previously cleared habitat (Campbell, Alexandra, and Curtis 2017). Furthermore, predictive models, such as the one presented here, could be incorporated into risk-based approaches (Stelzenmüller et al. 2018) which combine the probabilistic risk assessment with the characteristics and exposure sequences (these could be motivations for deforestation) and all factors which influence minimising risk (this may include regulatory instruments or socio-cultural values (Hauptmanns 2005).

It is clear, however, that probabilistic risk, does have implications for some vegetation communities in Queensland and should accompany diverse policy interventions to target specific regional issues. The Brigalow Belt and Mulga Lands were among the bioregions with the highest predicted probability of deforestation (90.5%, 97.7%). High predicted probabilities in these regions are not surprising because historical and modern clearance rates are high, similar to tropical deforestation hotspots in South America and south-east Asia (Lepers et al. 2005, Queensland Department of Environment and Science 2018). Indeed, since the mid-20th Century, mechanised clearing and a government settlement policy (the Brigalow Development Scheme) catalysed deforestation for agricultural development (Seabrook, McAlpine, and Fensham 2006). This was successful in establishing large agricultural areas in the Brigalow Belt and, subsequently, in the adjacent Mulga Lands. My results demonstrate that these bioregions are key target areas for future deforestation abatement policy as agricultural practices continue to have significant implications on landscapes within these bioregions. It may be useful for policies to consider socio-economic drivers of clearance and target the largest farmland parcels as farmlands expand around the outwardly (Seabrook, McAlpine, and Fensham 2008).

I found low maximum deforestation probability values in the Cape York, Central Queensland Coast and Wet Tropics Bioregions. Cape York is Queensland's most remote bioregion with a relatively unmodified landscape; however, Simmons *et al* (2018) found that remnant vegetation land deforestation rates increased substantially under policy reforms in 2016. Policy reforms (such as the re-introduction or revocation of certain clearing constraints) have implications for biodiversity (Reside et al. 2017) and, when introduced too quickly, may cause further undesired clearing through legislative uncertainty (Angelsen 2009). Resultantly, and to prevent 'panic clearing' (Bartel 2004) decisions around clearing policy and tenure restrictions must be considered carefully for these regions with clear communication around any proposed reform. The Central Queensland Coast is among Queensland's most heavily fragmented bioregions (Neldner, Laidlaw, et al. 2017) with historic and modern clearing transforming over 30% of its area. This bioregion, however, remains a stronghold for some threatened species (Garnett, Szabo, and Dutson 2011).

Australian expertise in revegetation, restoration and regeneration of landscapes would benefit this bioregion so long as the interventions have firm commitments in resourcing, appropriate scaling and proper management (Campbell, Alexandra, and Curtis 2017).

Finally, the Wet Tropics bioregion contains remarkable biodiversity reflecting the complex topography and high annual rainfall and, for this reason, was prioritised for conservation (Zachos and Habel 2011). The mountainous regions of the Wet Tropics are highly unsuitable for potential deforestation, and most of the lowland areas have been cleared to establish sugarcane, bananas, pasture and orchard crops thus reducing some original vegetation community types to <10% of their original range (Metcalfe and Ford 2009). My models suggest that deforestation does not directly threaten the mountainous landscapes; however, previous work has shown that landscape modification has saturated nearly all lowland areas (Queensland Department of Environment and Science 2018). There is a range of other management issues that drive regional biodiversity loss in the Wet Tropics including disease, invasive species and climate change. Three significant diseases impact biodiversity in the Wet Tropics: chytridiomycosis (or chytrid fungus), myrtle rust (*Puccinia psidii)* and phytophthora root rot with deleterious impact on species viability (McKnight et al. 2017, Worboys 2006, Pegg et al. 2018). All three diseases impact heavily on individual vitality, and, if left uncontrolled, can have devastating impacts on populations of native species. Furthermore, there are over 60 invasive species (such as gamba grass, *Andropogon gayanus,* and feral cats (*Felis catus)* (Harrison and Congdon 2002) in the Wet Tropics Bioregion (Poon et al. 2007, Stork, Goosem, and Turton 2011). Each invasive species potentially outcompetes or attacks native flora and fauna, resulting in the decline of native populations. Lastly, the multiplicative effect of climate change has serious implications for biodiversity in the Wet Tropics with modulations in the climatic factors determining rainforest probability (Williams, Bolitho, and Fox 2003). In summary, the Wet Tropics is subject to an array of threatening processes with severe consequences for biodiversity, but my results suggest that remaining forests in the Wet Tropics are unlikely to be impacted by deforestation. This region, therefore, would benefit from well-resourced and robust management instead of the establishment of new protected areas.

Under all scenarios, my modelling showed that some degree of deforestation may occur in all bioregions examined, but the extent is minimal. I found that the number of vegetation communities impacted by future deforestation ranged from 18% under the likely scenario (i.e. assuming deforestation only occurs in areas with probabilities above the upper whisker) up to 55% under the unlikely scenario. Importantly, this range of values demonstrates that the threshold for reclassification of deforestation probability values must be carefully considered. In my unlikely scenario, probability values as low as 3% were included in the binary reclassified (cleared/not cleared) layer. While this is useful for presenting the results of an unlikely scenario (*i.e.* if deforestation was not restricted and fully saturated all areas), this scenario is likely to over-estimate the potential future impact of deforestation. In the moderate scenario, I reclassified all probability values above the upper quartile as “likely to be cleared.” I found that this reduced the estimated area of potential deforestation impact by over 10,000 ha further demonstrating the value of producing a range of reclassification strategies when working with continuous data.

Under the likely scenario, future deforestation may only impact 380,000 ha of native remnant vegetation. Currently, Queensland is experiencing land clearing at a rate of 400,000 ha per year. Of this, 78,000 ha is native remnant vegetation (or vegetation which has not been previously cleared) (Department of Science 1988-2016). However, policies that consider predictive methods like those presented here could be useful for preventing the transfer of vegetation communities into higher threat categorised (*ie* become more endangered) (Evans 2016).

Deforestation in portions of regional ecosystems has important implications for habitat fragmentation. Although the effects of habitat fragmentation have been described as a panchreston (Lindenmayer and Fischer 2013) with recent speculation due to the allegedly inappropriate extrapolation from patch size and isolation to fragmentation (Fahrig 2019), habitat fragmentation remains one of conservation’s most studied threatening processes (Nghiem et al. 2016). Previous studies have suggested habitat fragmentation has negative impacts on biodiversity by catalysing future habitat loss (Collinge 2009), localising extinctions on patches in the presence of pathogens (McCallum and Dobson 2002), introducing edge effects, and altering nutrient cycles to ultimately reduce biodiversity by 13-75% (Haddad, Brudvig, Clobert, Davies, Gonzalez, Holt, Lovejoy, Sexton, Austin, Collins, et al. 2015). Thus, even moderate amounts of clearing on Queensland’s vegetation communities have important ecological consequences that are not yet understood. Predicting deforestation before it occurs provides the opportunity to understand whether or not potential deforestation will, in fact, negatively affect vegetation communities.

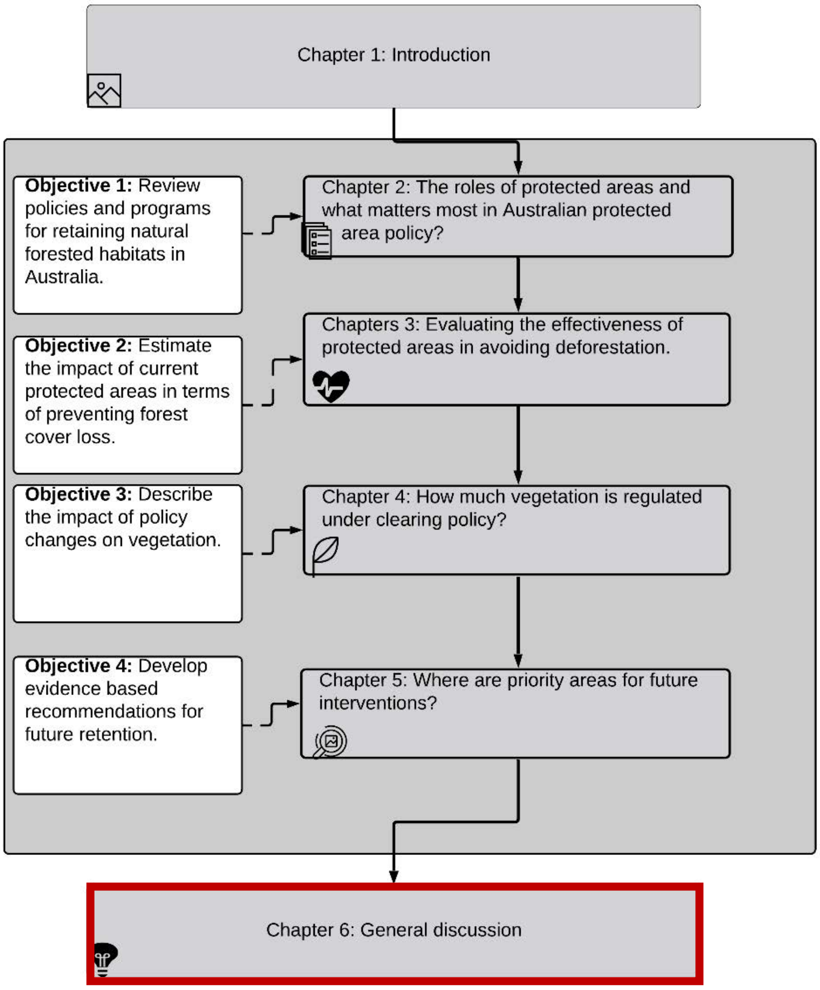
Making a quantifiable difference as a result of a policy or other intervention is a crucial method in demonstrating impact (Khandker, Koolwal, and Samad 2010, Pressey, Visconti, and Ferraro 2015). In this context, I provide a predictive dataset that can be used to predict where a change in vegetation management status could possibly occur. In my analysis, I documented all the vegetation communities with probable status changes (**Appendix 5.6-5.8)** as a result of future deforestation. In this context, a change of status implies the increased vulnerability of a vegetation community to extinction. Policy interventions that target these regional ecosystems will contribute to impact in terms of avoided habitat loss, and those vegetation communities which are not likely to change status may benefit from other land management strategies (*i.e.* invasive species management). In the current context, least concern vegetation communities are not regulated under Queensland's vegetation management or biodiversity legislation, and their susceptibility to loss is not currently considered (State Government of Queensland 2019). I identified several vegetation communities that are likely to migrate from least concern to an of concern or endangered status under each scenario. Identifying these communities is essential for future interventions because they are not currently being assessed or monitored by current vegetation or biodiversity legislation. Modelling potential deforestation in this context represents a novel strategy for maximising the impact of policies aimed at minimising habitat loss. I recommend that such predicative analysis is incorporated into the definition classes of VMA statuses to prevent a change in vegetation management status from occurring.

Limitations and future work

In Chapter 5, I have demonstrated that freely available datasets provide valuable insights about the trends and correlation of deforestation drivers that might have otherwise been missed, significant advances have been made in the deforestation modelling literature. The methods applied in this constitute a well understood and scientifically sound technique. This approach was chosen because the models are easy to implement, can be updated quickly as freely available datasets are updated and because they are ideal for understanding the simple correlations between variables that can provide insights into the drivers of deforestation. However, additional techniques, including artificial neural networks (Ahmadi 2018) and Bayesian networks (Silva et al. 2019) also warrant evaluation (Mayfield et al. 2016). Tree-based methodologies (Zanella et al. 2017) have also been identified as potentially suitable candidates and have recently started appearing in deforestation modelling literature (de Souza and De Marco 2018). My models have incorporated known drivers of deforestation in this context based on a comprehensive literature search. To avoid over-fitting, I have tried to limit my predictor co-variates which directly relate to climate, topography and land productivity concerning cattle grazing. Future models could consider incorporating the Queensland Government's Agricultural Land Audit data (Government. 2013b) (DAFF 2013) which describes land capability for cropping. As land capability is a function of climatic conditions, this dataset was not used. Furthermore, distance to currently cleared areas could be investigated as a predictor as well as cost-distance to roads or markets (rather than Euclidean distance).

Vegetation management status adopts a single area (10,000ha) and a few target percentage goals for classifying regional ecosystems (e.g., 30% of historic extent). Still, there is limited scientific justification or rationale to support these definitions. My analysis is consistent with the thresholds provided in the legislation. Nevertheless, I note that there is a clear need to understand the viability of each regional ecosystem in terms of the remaining extent (Neely et al. 2001). In the absence of such an assessment, there is a risk that threats, such as deforestation, will be under-estimated, and the biodiversity consequences will go unprevented. Vegetation management status also applies to the level of degradation affecting the regional ecosystem. Modelling degradation was outside the scope of this project. Here, I focused only on changes to the total area of the regional ecosystem, and this may under-estimate regional ecosystems, which are likely to change status. Future work should consider modelling degradation on regional ecosystems.

Chapter 6. General Discussion



Overview of research findings

The overarching goal of this thesis is to evaluate the current policies and practices used in forest retention and to supplement the systematic conservation planning approach to maximise impact. The effectiveness of conservation outcomes is best understood within the context of counterfactual scenarios (Adams, Barnes, and Pressey 2019). Counterfactual scenarios are a measurement of outcomes in the absence of an intervention. Over thirty years ago, the first calls for counterfactual evaluation appeared in the scientific literature; however, such analyses remain rare in conservation literature. Resultantly, conservation policies and practices aimed at protecting biodiversity are ineffective for strategically and efficiently abating current and increasing biodiversity decline.

Prior to this research, there was no comprehensive research on the effectiveness of policies in a single conservation context. Throughout this thesis, I have addressed four significant knowledge gaps corresponding to four research objectives (**Figure 6.1**). The contextual information relating to the significance of these knowledge gaps is provided in **Chapter 1**. In subsequent chapters, (**Chapters 2-5**), I presented research to address each of these objectives. In this chapter, I first summarise the key findings for each of these chapters and how results correspond to research objectives. I then discuss the limitations of research in this thesis and identify further knowledge gaps to be addressed by future work.

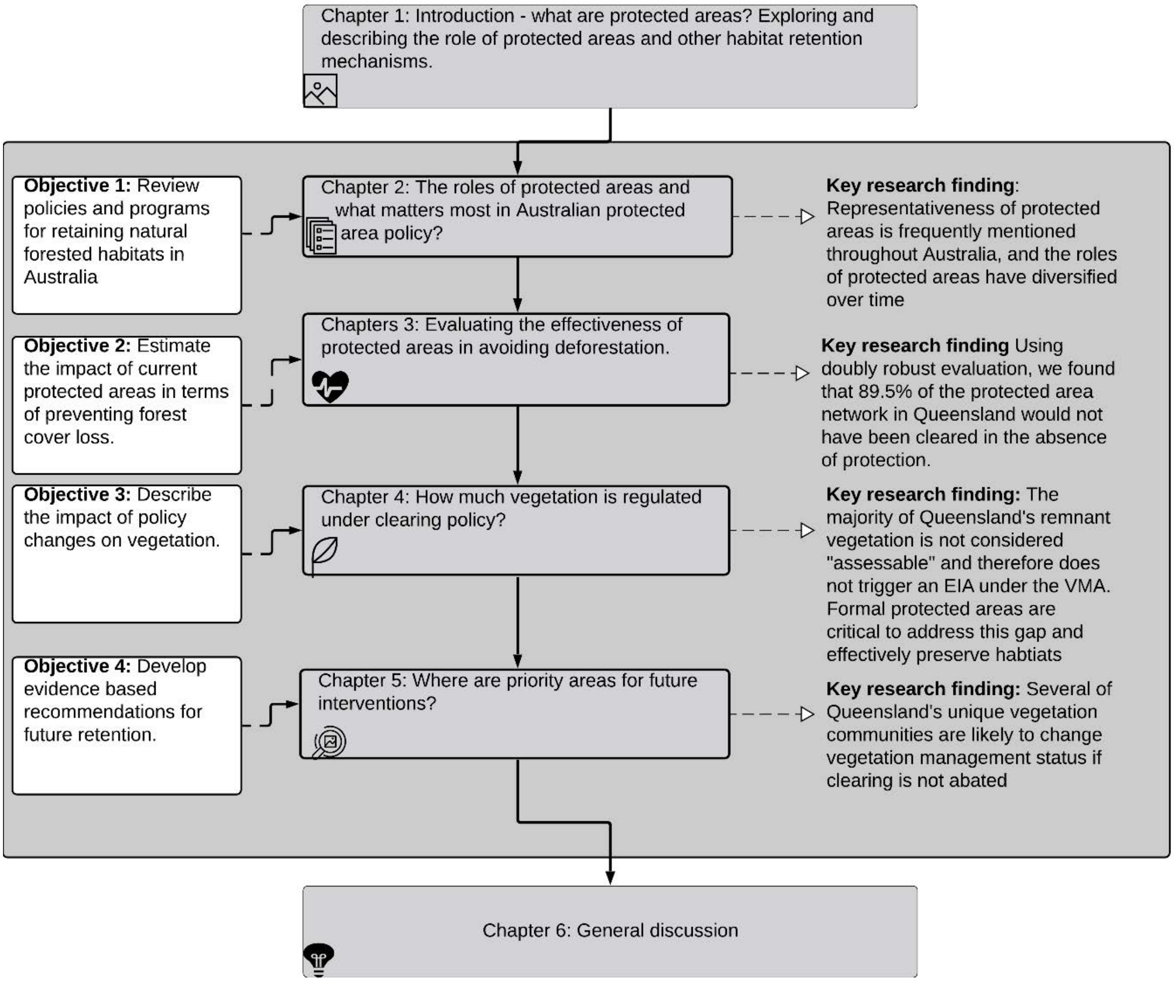


Figure 6-1: A schematic diagram of knowledge gaps and objectives addressed in this thesis. This figure represents which chapters contribute to each research objective and the key research finding for each objective.

Original contributions of my research

Australia was an early adopter of attempts to establish a reserve system based on systematic conservation planning principles. Widely adopted protection strategies (such as area or representation targets) are the primary target of considerable resourcing across the globe. The criteria used for park selection precipitate naturally from the transmission of social values (Hellström and Rytilä 1998) and attention to fluctuations in these pluralistic criteria is necessary for the design of future policies. Given the imminence and severity of current biodiversity declines, it is imperative to understand the key concepts within conservation policies and how these are distributed across time and jurisdiction. I found representativeness of species habitat types was found to be the key consideration driving the creation of protected areas, and the least common consideration was avoiding the loss of species or habitats (**Chapter 2, Figure 2-2)**. This is a problem for two reasons: 1) If biodiversity features are continuously lost because of deforestation, then we can assume that the protected area network cannot be truly representative. 2) Representativeness of forest communities cannot be comprehensively achieved across Australian States and Territories because of inconsistencies in datasets across the nation (**Appendix 2, Section 2.3)**. Furthermore, I demonstrate throughout this thesis that representativeness cannot address or anticipate threats and the impact of threats on biodiversity. Consequently, by prioritizing representativeness as a goal in its own right, conservation interventions, such as protected areas, may trade away effectiveness, efficiency, and urgency for biodiversity outcomes (Ferraro 2009). Although representativeness is an important conservation outcome, the scientific underpinning and ultimate conservation value of these targets have fallen under recent scrutiny (Soulé and Sanjayan 1998, Agardy, Claudet, and Day 2016). These studies suggest that representativeness targets may be obfuscated by politically expedient objectives where charismatic species or communities are primarily target. The potential outcome of this may well mean that species or communities which require urgent intervention are not prioritized.

It is important to understand how well protected areas are performing in terms of avoiding threatening processes. If they are ill-performing, then the strategies guiding their selection require a restructuring. To understand the effectiveness of protected areas, in Chapter 3, I used a quasi-experimental approach. This method is standard across the medical (Hill 2008) and economic literature (Morgan and Baylis 2017), but relatively uncommon in conservation literature (Ferraro 2009). Using statistical matching, I found that 89.5% of strictly protected areas would not have been cleared even in the absence of protection (**Chapter 3, Table 3-3, Figure 3-4)**. This means that protection some difference to deforestation in these areas. Without statistical matching, the estimated impact was twice that estimated with matching, reinforcing the need for robust evaluation to estimate avoided loss accurately.

As protected areas are demonstrably ineffective guarantees of preventing deforestation, I was interested in understanding the performance of the other common policy lever, clearing policies. Consequently, I analysed the Vegetation Management Act (**Chapter 3**) in three time-steps for evidence of policy changes relating to how much vegetation can be cleared **(Chapter 3, Table 4-3, Figures A4-1 -to A4-2)**. My analysis revealed that clearing guidelines regulate clearing where the vegetation overlaps or contains one or more of seven biophysical features or vegetation characteristics (*i.e.* proximity to wetlands or vegetation type, **Figures A4-1 to A4-5)**. A lack of assessment means that guidelines rely heavily on or are fundamentally constrained by target features rather than taking preventative or preemptive approaches to vegetation control. In each scenario, I identified extensive areas in Queensland that lack such spatial or biophysical characteristics and are, therefore, not considered assessable. Spatially, this means that most of

Queensland's vegetation does not have biophysical, ecological or spatial features that would trigger an environmental assessment. My analysis also confirms that rapid changes in policy regimes have considerably altered the purposes for which a proponent may clear their land (Reside et al. 2017). Expeditious policy changes risk eroding public trust in political regimes (Nelson et al. 2017) and can also result in the phenomena known as "panic-clearing" where vegetation clearing rates rise as landholders anticipate a change to clearing restrictions.

The Queensland Government, through its extensive scientific consultation process in 2018, has improved its vegetation management procedures substantially (Butler et al. 2018). However, current political tension around vegetation clearing necessitates public consultation and participation in future policy changes (Simmons 2020). In Chapters 2, 3 and 4, I discussed and provided evidence for: i) the rise of vegetation clearing, ii) the ineffectiveness of protected areas in avoiding deforestation and iii) the extent of vegetation not considered assessable by vegetation management. Collectively these chapters demonstrate that native vegetation in Queensland remains exposed to further loss through clearing. To remedy this and to assist decision-makers with future protected area or vegetation management policy, I modelled where future clearing is likely to occur in Queensland and assessed its implications for vegetation communities

Spatially explicit modelling is an important tool for policymakers across multiple disciplines. Modelling provides insight into potential outcomes given a particular set of parameters and can be useful in informing policy interventions (Tulloch, Tulloch, et al. 2015). In Chapter 5, I model three threat scenarios (Sahai and Khurshid 1995) to identify vegetation communities under at risk for changing status. I demonstrate the utility of combining spatial modelling with policy definitions to provide tangible recommendations for future management. Using three threat scenarios (unlikely, moderate, likely), I identified 152, 126 and 12 vegetation communities that may change vegetation management status (*i.e.* become more likely to go extinct) if clearing is unabated (**Chapter 5, Table 5-4)**. All vegetation communities at risk of future clearing and the extent to which they overlap with the predicted deforestation front are included in Appendix 5. Importantly, this study illuminates the mechanisms by which protected areas can affect environmental outcomes and provides a platform from which future protected areas can be assessed.

Throughout this thesis, I have demonstrated that the current governance and management frameworks are moderately equipped to prevent increasing clearing across the State, and that land-clearing as a single threat is likely to have some impact on vegetation communities across the State. However, whilst it is intuitive to assume that more resourcing or actions directed towards conservation will yield positive outcomes for biodiversity, the absolute value of the input depends on a clear articulation of what the resource or action is trying to achieve and then actioned accordingly (Pressey, Weeks, and Gurney 2017). In the case of vegetation communities, I recommend that broad commitments relating to simple area or number of species are replaced with actionable decisions capturing the underlying drivers of species and ecosystem decline and robust methods for implementing and evaluating the effectiveness of protected areas in achieving the range of priorities for which they are established. In the absence of a robust, interdisciplinary evaluation against strategic priorities, protected areas may well be ineffective strategies, outpaced and overwhelmed by the sheer scale, growth and complexity of the obstacles facing biodiversity (Balmford 2006). So, while establishing more area-reserved may assist in achieving policy targets, the socio-ecological attributes we value most may decline under such policy paradigms. Alternative arrangements that integrate a holistic perspective to threat anticipation, restoration and management are a key priority moving forward.

Management implications

Governance is the cumulative management of common affairs by individuals and institutions (both public and private), and it is purposed with representing the interests of all parties. Governance is considered to be 'good' if it is participatory, transparent and accountable (United Nations Development Program 1997, Harrison and Sayogo 2014). Using information developed in this thesis, I provide a summary of my major findings and some broad principles to foster good governance in Queensland Australia: i) maintain public records regarding candidate protected areas and allow public comment on negotiations; ii) a commitment to robust impact evaluations against policy objectives; iii) a commitment to strategic, purposive identification of candidate protected areas; iv) consider the cumulative impact on vegetation communities when assessing clearing applications.

Principle 1: Maintain public records

The first principle that I recommend increasing transparency is a requirement for all information on negotiations for candidate protected areas are available to the public and that the public is permitted to provide comments and provide input into negotiations. Previous research had identified and described instances where the reservation for conservation purposes may be side-lined in favour of the State's economic interests resulting in a residual protected area network (Pressey et al. 2002). To avoid a residual network and achieve more effective vegetation management, publicly available information regarding the negotiations over land for protection or commercialisation is urgently needed. For example, the management category for a candidate protected area is often declared relative to the types of activities already occurring on the land when it was acquired. For example, the land is typically declared as a resource reserve if there was an extractive authority (mining lease or mining claim) on the land at the time of purpose.

Further, there may be a tendency for lower IUCN statuses to be declared on land which already supports recreational uses inconsistent with the principles required for national parks (horseback riding, mountain biking, grazing and eco-tourism facilities). This sequence, therefore, does not necessarily prohibit existing activities in favour of biodiversity outcomes, rather it legitimises such activities by fitting a protected area class around current uses. Indeed, the logic behind this sequence may be entirely sound, but, without a clear and transparent record of the decision-making, the public is left with speculation and opacity. As demonstrated in **Chapter 3**, the protected area network has made little impact in terms of avoiding deforestation. A clear and transparent record of acquisitions could be highly valuable in framing future evaluations of the estate.

Principle 2: Commitment to robust impact evaluations

Accountability in public sectors can be bolstered by requiring regular reporting on the effectiveness of conservation interventions in meeting their objectives. For example, in support of the expanded roles as are necessary for modern protected areas, legislation now can create multiple tenures of protected areas (Watson et al. 2014b). Complex governance arrangements, resulting from a long history of protected area development (**Chapter 1**), within the Department support these tenures (**Chapter 2, Appendix 1**). Morrison (2017) found that as the complexities of governance of the Great Barrier Reef increased, its effectiveness diminished. In parallel, the governance arrangements for terrestrial protected areas in Queensland has grown increasingly complex, and the effectiveness of protected areas to meet each of these roles is unknown. Specifically, there are no reporting requirements for evaluating the efficacy of candidate or current protected areas in fulfilling these objectives.

In assessing candidate protected areas and reporting on the effectiveness of the current network, a more nuanced approach would consider what would happen to the parcel of land if it is not protected. For candidate protected areas; however, a significant limitation to acquisition is the cost of the land parcel. If the parcel too expensive, then it may not be acquired, despite its capacity to fulfill policy objectives or its conservation value. While financial management is crucial to any effective business, such cost-minimising treatment assumes that protected areas fail to provide a return on investment. Previous rebuttals to this argument describe the value of protected areas values concerning tourism (Carlsen and Wood 2004, Lee and Han 2002) and ecosystem services (De Groot, Wilson, and Boumans 2002). While these roles are undeniably important, their usefulness as a valuation instrument is underpinned by the assumptions of contingent valuation, where social and cultural contexts attach value to ecosystem goods and services (Gatto and De Leo 2000).

Alternatively, it may be useful for Governments to robust impact evaluations of the candidate and current protected areas in fulfilling their objectives. Such evaluations can be used as a negotiation tool when the issue of costing is raised (Adams, Game, and Bode 2014). That is, evaluators must assess whether the acquisition is necessary to ensure habitat conservation on candidate land parcel. This facilitates a quantifiable argument for or against the reservation of a parcel. Such an evaluation can be used to assess a parcel's merit and potentially provide a cost-benefit analysis for including that parcel in the network by crucially answering the question: "What would happen if I did nothing?" Such reporting can be an invaluable negotiation tool for future assets and resourcing, and fill a fundamental knowledge gap concerning how well the current network is doing in terms of fulfilling its objectives.

Principle 3: A commitment to strategic, purposive identification of candidate protected areas

Conservation strategies are highly variable and depend on a variety of factors. These factors include targeted biodiversity, costs, the spatial and temporal distribution of threats, and the timeframe given to achieve the desired outcome. The combination or prevalence of these factors will vary with the scale of the planning region and its historical or socioeconomic circumstances. Thus, the relationship between social and environmental systems transgresses the boundaries of academic disciplines and requires cross-disciplinary approaches when designing an intervention. Evaluating the impact of an intervention using a casual model is a critical step in evidence-based decision-making about whether, when, and where to intervene (Game et al. 2018).

Australia has taken strong action on biodiversity decline by setting up an internationally renowned system of governance (Holley, Gunningham, and Shearing 2013). The use of targets is a widely recognised approach for tracking progress. However, overcoming the complex socioecological problems associated with creating a future strategy for protection needs will require setting robust and measurable targets (Pressey, Visconti, and Ferraro 2015, Pressey, Weeks, and Gurney 2017). Modern target settings tend to focus on targets that are SMART (specific, measurable, ambitious, realistic and time-bound) (UNEP 2011). SMART targets are advantageous because they hold parties accountable by determining if and when a target is met. Historically, SMART targets were used in the Montreal Protocol and were effective in phasing out chlorofluorocarbons (CFCs) (Skjærseth 2012). The issue of CFCs, however, was relatively noncontentious because the economic, ecological and social benefits of eliminating the ozone-depleting pollutant were clear. In the case of contentious issues, a more nuanced approach involving specific attention to the development of targets is needed (Maxwell et al. 2015). This can be achieved through public participatory approaches (Benham and Hussey 2018). Previous studies have demonstrated that participatory governance can strengthen public decisions by incorporating local knowledge into governance processes, reduce conflict between stakeholders, and building institutional trust (Beierle 2010, Fischer 2000). Public deliberative forums can provide considerable insight into community concerns and preferences concerning vegetation management, and this information can be fed to environmental managers and policymakers. In the context of future strategies for protected areas, SMART targets formed within a deliberative forum could substantially benefit future strategies.

Principle 4: Consider the cumulative impact on vegetation communities when assessing clearing applications.

Conservation actions are frequently at odds with economic growth, causing a profoundly ingrained conflict between conservationists and developers (Game et al. 2014). Modern conservation efforts are concerned with balancing natural resource objectives with conservation outcomes. Notably, the need to manage the cumulative effects of multiple human pressures has been long recognised in resource management. For example, the United States explicitly requires an assessment of multiple impacts before issuing permits for new developments under the National Environmental Protection Act (NEPA 1969). Similar laws in Canada and Europe have also captured and codified cumulative impacts (Halpern and Fujita 2013). While historical methods for addressing the cumulative impacts of multiple threats include cataloging the impacts of single stressors and marking the overlap of multiple, such approaches are typically *ad hoc* and fail to consider the interactions between threatening processes. A more nuanced, such as vulnerability weighting, translates the intensity of a stressor into its predicted impact and then sums the expected impacts into a total score (Halpern and Fujita 2013). In this thesis, I have provided a cumulative perspective of the state of vegetation by assessing the performance of both vegetation management (**Chapter 4**) and protected areas (**Chapter 3**). This is consistent with the approach taken by the Vegetation Management Act, 1999 in so much as cumulative impacts are considered relative to the extent of a vegetation community remaining since European settlement. However, this thesis only considers threats to vegetation under the lens of deforestation. In the absence of a cumulative impact assessment to multiple land uses and how these change over time, data supporting the on-going productivity and ecological viability of the land is unknown. This may force management to rely on siloed datasets which are not reflective of the on-ground reality, and further entrench the conflict between natural resource management and conservation. Thus, the imperative needs to be building on Queensland's vast wealth of knowledge and experts to create the best possible methods for anticipating and managing cumulative impacts across the range of land uses while also ensuring that land managers are encouraged for using ecologically responsible strategies.

Future research directions

Several future research directions arise from this work. I focused exclusively on the governance of terrestrial vegetation communities at a State level. International treaties and Federal legislation influence the course of policies in Queensland. The value of this research is that it provides a comprehensive case-study perspective on vegetation governance; however, further research that explores the synergies and influence of other arrangements could bolster the findings herein. Furthermore, there is a clear need for more detailed research into the conflict around vegetation management in Queensland. While the current vegetation management policies were developed after extensive scientific consultation, they are still considered contentious in agricultural sectors. Specifically, discourse analysis in a public facilitated workshop environment could provide substantial insights into the heart of these conflicts.

At the heart of the environmental conflict is a perceived misalignment between the stakeholders of a natural resource. Resolving this conflict requires continued protection, management and restoration to create representative and functional habitat networks. This calls for the establishment of neutral fora and platforms for collaboration and partnership development to improve integration among different actors. To ensure conservation efforts are considered equitable, community input is critical to legitimising governance initiatives. Legitimacy in this context redefines “acceptability” through public perception as well as scientific criteria (Shepherd and Bowler 1997) and can be achieved through public participatory approaches (Benham 2017).

Furthermore, despite Federal (Secretariat for the Convention on Biological Diversity 2016, UNEP 2011) and State (Queensland Government. 2017) commitments to increase land in protected area networks, the negotiations and processes supporting declarations are missing from the public record. To fill this gap and describe the process of creating protected areas for the public record, I recommend future research using an expert elicitation process. Experts, in this context, would refer to individuals with substantive knowledge and information on a topic that is not commonly known by others (Burgman 2005), and data gathered from experts is often the only or the most reliable information available (Carwardine et al. 2011).

Impact in terms of avoiding deforestation is not a panacea as it does not face externalities such as climate change. Thus, a significant and unresolved gap in this thesis is the problem of climate change and its implications for future vegetation communities. Previous research has investigated how species may shift as a result of climate change (Graham et al. 2019), and climate change may affect the regularity of future catastrophic events (Clarke et al. 2019). Climate change is increasingly important as Australia begins to face the reality of a changing climate. Starting in

September 2019, nearly 30 million acres of Australia's eastern coast burned. Figures calculated by the Federal Government indicate that 136 threatened species and 84 nationally listed threatened ecological communities occur within fire-affected (Australian Government 2020b) areas. The catastrophic reality of these fires was a culmination of record hot and dry conditions across the country. Climate change has serious implications for future biodiversity retention, and it is important to note the reality of forest loss is not limited to land clearing for development. Nevertheless, identifying and equitably managing trade-off using impact evaluation can usefully inform structured decision making within governance frameworks (Ohlson, McKinnon, and Hirsch 2005, Gregory and Long 2009).

Conclusion

Deforestation is fuelled by the increasing export of primary commodities and increasing demand for timber and agricultural products in a globalizing world (Kissinger, Herold, and De Sy 2012), and is a globally significant threat to ecological integrity (Evans et al. 2017) We also know that humanity possesses a profound capacity to shape ecosystems (Kissinger, Herold, and De Sy 2012) and remarkable capacity for global unification in order to conserve them (UNEP 2011, United Nations 2014, 2018). As a global society, our greatest challenges are ahead. Do we continue to push politically expedient conservation policies as we have done in the past? Or, do we modify our approach to forest governance, managing human behaviour in a manner that steers us towards impactful outcomes? Whichever path we take, there is one certainty – forested habitats will change in response to our actions.

This thesis has examined the two primary policy levers aimed at reducing deforestation – protection and vegetation management. In doing so, I identified several challenges and opportunities for future policy development. At present, the most significant challenge is a failure to document the social, economic and environmental impacts of a conservation policy. Thus, despite enormous funding on protection and restoration, biodiversity continues to decline. This demonstrates a clear need for measuring the impact and effectiveness of the conservation outcomes required by policy. It is of utmost importance to frame conservation outcomes in terms of impact and initiate an evaluation procedure that reports on what would have happened in the absence of a conservation policy.

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Appendices

Red flowering gum. Used with permission from artist Jennifer Ross (2019)

Appendix 1: Supporting information for Chapter 1

A1.2 Types of protected areas in Queensland and their permissible activities

Queensland protected area tenure types. *Management principles from *Queensland Nature Conservation Act, 1992*. #Management Principles from *Queensland Forestry Act, 1959*. + (International Union for the Conservation of Nature 2018), [i](Queensland Government 1992)

Table A1-1: Queensland protected area tenure types. *Management principles from Queensland Nature Conservation Act, 1992. #Management Principles from Queensland Forestry Act, 1959. +(International Union for the Conservation of Nature 2018), [i](Queensland Government 1992)

Tenure Type	Abrv.	Management Principles[i]	IUCN Class	IUCN Definition+	Activities permitted
Conservation Park*	CP	i) Conserve and present the area's cultural and natural resources and their values ii) Provide for the permanent conservation of the area's natural condition to the greatest possible extent iii) Provide opportunities for educational and recreational activities consistent with the area's natural and cultural resources and values iv) Ensure that any commercial use of the area's natural resources, including fishing and grazing, is ecologically sustainable.	III	Focused on one or more prominent natural feature (*i.e.* geological feature, a sacred site, or another distinguished land/sea form) and its associated ecology rather than the broader landscape.	- Grazing (s 58) - Dog walking - Apiary (s 31) - Controlling Activity (s 48(1)) - Take permitted animals (s 49) - Stock mustering (s 60) - Travelling stock (s 62) - Horse riding (s 131(2d))
Forest Reserve*	FR	i) Protect the biological diversity, cultural resources and values and conservation values of land that is included in the reserve ii) Provide for the continuation of lawful land-use iii) Ensure all use is ecologically sustainable	II, VI	II - Large natural or near natural areas set aside to protect large-scale ecological processes along with the complement of species and ecosystem characteristics of the area VI - Large areas of natural or near natural areas set aside to conserve ecosystems and habitats together and associated cultural values and traditional natural resource management systems. A proportion is usually under sustainable natural resource management	- Controlling Activity (s 48(1)) - Stock mustering (s 60) - Travelling stock (s 62)

Tenure Type	Abrv.	iv)	Management Principles[i]	IUCN Class	IUCN Definition+	- Activities permitted
National Park*	NP	i) ii) iii) iv)	Protect the natural condition, cultural resources and values Present the area's cultural and natural resources and their values Ensure the only uses are nature-based and ecologically sustainable Provide opportunities for ecotourism	II	Large natural or near natural areas set aside to protect large-scale ecological processes along with the complement of species and ecosystem characteristics of the area	- Service or ecotourism facility (s 17) - Controlling Activity (s 48(1)) - Take permitted animals (s 49) - Stock mustering (s 60) - Travelling stock (s 62) - Horse riding (s 131(2d))
National Park – Scientific*	NS	i) ii) iii)	Protect the area's scientific values, in particularly: - Ensuring natural processes are unaffected in this area - Protect the area's biological diversity to the greatest possible extent. Allow controlled scientific study Where threatened wildlife is significant, management may include the: - manipulation of the wildlife's habitat; and - control of threatening processes relating to the wildlife, including threatening processes caused by other wildlife	IA	Called indispensable reference sites for scientific research. These strictly protected areas are set aside to protect biodiversity and also possibly geological/geomorphical features. Human visitation, use and impacts are strictly controlled and limited to ensure protection.	- Controlling Activity (s 48(1)) - Stock mustering (s 60)
National Park – Aboriginal Land*	NY	i) ii)	To be managed as a national park Consistent with Aboriginal tradition applicable to the area	II	Large natural or near natural areas set aside to protect large-scale ecological processes along with the complement of species and ecosystem characteristics of the area	- Controlling Activity (s 48(1)) - Stock mustering (s 60) - Travelling stock (s 62)
Resource Reserve*	RR	i) ii) iii) iv)	Recognise and, if appropriate, protect the area's cultural and natural resources Provided for the controlled use of cultural and natural resources Ensure that the area is maintained predominantly in its natural condition Not allow the felling of commercial timber	III, VI	III - Focused on one or more prominent natural feature (*i.e.* geological feature, a sacred site, or other distinguished land/sea form) and its associated ecology rather than the broader landscape. VI - Large areas of natural or near natural areas set aside to conserve ecosystems and habitats together and associated cultural values and traditional natural resource management systems. A proportion is usually under sustainable natural resource management	- Mining (s 21) - Stock grazing (s 58) - Dog walking (s 154) - Apiary (31) - Controlling Activity (s 48(1)) - Take permitted animals (s 49) - Stock mustering (s 60) - Travelling stock (s 62) - Horse riding (s 131(2d))

Tenure Type	Abrv.	i)	Management Principles[i]	IUCN Class	IUCN Definition+	- Activities permitted
State Forest#	SF	ii)	The permanent reservation of such areas for the purpose of producing timber and associated products in perpetuity and protecting a watershed therein		To protect natural ecosystems and use natural resources sustainably, when conservation and sustainable use can be mutually beneficial.	- Mining (s 37) - Stock grazing (s 35) - Apiary (35)
Timber Reserve#	TR	i)	The permanent reservation of such areas for the purpose of producing timber and associated products in perpetuity and protecting a watershed therein		To protect natural ecosystems and use natural resources sustainably, when conservation and sustainable use can be mutually beneficial.	- Mining (s 37) - Stock grazing (s 35) - Apiary (35)

A1.2 A historical review of Queensland's protected areas

Historical reviews are essential for providing a reference and an aid to research policy development. While previous studies have reviewed modern policies relating to protected areas (Norton 2013, Sattler 2014), none have comprehensively reviewed all biodiversity conservation legislation since European settlement and described when values captured in polices first appeared. Here, I focus the scope of this review to Acts responsible for both the creation of protected areas and reserves and those that manage biodiversity. I summarise the roles of required of protected areas and reserves and describe their emergence in Queensland's legislation. Current Queensland protected area legislation is unified with biodiversity legislation. Here, I track biodiversity legislation through time in conjunction with protected area legislation.

Recognising that statutory frameworks applying to marine and terrestrial protected areas and others which apply to cultural or heritage values, these are beyond the scope of this review. I will, therefore, limit our discussion only to legislation applicable terrestrial protected areas gazetted for biodiversity conservation or cultural values. In this context, we refer to areas gazetted under the Nature Conservation Act, 1992 (NCA) as protected areas. State Forest and Timber Reserves declared under the Crowns Alienation Act, 1868, Land Act, 1897 or Forestry Act, 1959 are referred to as reserves.

I identified the initial legislation responsible for the regulation of forestry reserves and native species and then tracked the Acts after repeal and replacement. I sourced all legislation from historical archives in Federal (Australasian Legal Information Institute 2019) and State (Queensland Government 2018b) databases. I further sourced historical gazette notices (or public notices regarding the formal declaration of a park or reserve) from archives held at the Department of Environment and Science to confirm Queensland's first National Parks unequivocally. I comment on the growth of the protected area network in terms of the total amount in protected areas per decade. Growth data were retrieved from (Pressey *in prep*). In this article, the authors investigated the extent to which residual landscapes were represented in the protected area estate per decade.

The Crowns Alienation Act

The first legislative instrument to regulate forestry resources in Queensland was the *Crowns Alienation Act 1868 (31 Vic No 46)*. (**Figure 1-4**). Therein, powers were delegated to the Governor in Council to dedicate Crown Land as a reserve for public purposes. It was under Crowns Act that the earliest known Timber Reserves were declared at Fraser Island, Maryborough, Myrtle Creek, Mount Urah and the Barron River. These Timber Reserves represented the first control of indiscriminate harvesting in Queensland. The moratoriums on some of these reserves lapsed, and they were eventually converted into other land-use purposes (*ie* National Parks, recreation areas or mining leases). The Crowns Act was historically significant because considerable areas of Crown Land have been (and continue to be) assimilated into the protected area network (Frawley 1988).

Queensland's first National Parks

In 1897, the *Land Act, 1897* was passed to consolidate and amend existing laws regarding land alienation (passing of Crown Land to private ownership by grant or purchase) or the leasing and occupation of Crown Lands (**Figure 1-4**). Subdivision III of the Land Act maintained the power to grant reserves for public purposes, and it was under this Act that the definition of "public purposes" was expanded for the first time to include "camping places" making public recreation a priority for landscape reservation. Contrary to the popular notion that Witches Falls was Queensland's first National Park (Sattler 2014), gazette records retrieved from the Queensland Government Archives clearly show that on 22nd September 1900 and under Sections 19 and 190 of *The Land Act 1897 (*61 Vic, No. 25*),* Barron Falls in Far North Queensland became the State's first National Park. In the same year, the purpose of national parks was also expanded to scientific research (1 Geo V, No 15). Despite faceting tenures and objectives of reserves, there was not, yet, a formal division of Government purposed with the management of areas set aside for recreational or scientific purposes.

Thus, land in Queensland was administered under the Land Act, but it was not the responsibility of the Land Act to manage and establish new National Parks or State Forests. In 1906, the *State Forests and National Parks Act (*SFNP*)* (6 Edw VII, No 20) was proclaimed provided a new administration to establish conservation areas. SFNP provided power to the Governor in Council to declare Crown Land as National Park or State Forest and to appoint officers to assist with the execution of the SFNP Act. However, it wasn't for another 53 years that an agency to manage forests, called the Department of Forestry, was created (*Forestry Act 1959*, 8 Eliz II, No 58). During this time, the management of National Parks was handled by the National Parks Branch of the Department of Forestry. In later years, the SFNP was supported by the *Fauna Conservation Act 1952*, and, under this Act, the first voluntary and private refuges for nature were authorised.

Biological Diversity

As was the case for protected areas, legislation to protect native animals has also diversified over time. The first Act to protect species, the *Native Bird Protection Act 1877* (41 Vic No. 7) was proclaimed in 1877 (**Figure 1-4**) after acknowledging the rapid decline of native birds (Chisholm 1922, Foale 2005). The objective of the Act was to protect listed native birds and their progeny. The Act was quickly amended, however, to allow landowners and their employees or slaves to kill native birds suspected of damaging crops (Legislative Council, 1877). Thus, while some native birds were protected from harvesting and hunting, indiscriminate harvesting and hunting for all other native animals remained unregulated. Thirty years later, the Native Animals Protection Act 1906 (6 Edw VII, No 5) was passed. This legislation did not protect for all native species, only those listed in the Schedule of the Act and were (as then known): Tree Kangaroo (all species of Dendrolagus); Wombat (*Phascolomys gilespieii*); Duck Mole or Platypus (*Ornithorhynchus anatinus*) Hedgehog or Echidna (*Echidna aculeata*) Flying Squirrel or Opossum Mouse (*Acrobates pygmreus*). A few years later, the act was amended to regulate harvesting possums and kolas (s2) for the fur trade. This period represents an interesting conflict as some native species were increasing in their protection while others were being deliberately persecuted. That is, concurrently to increased regulation on the above-listed animals, the killing of kangaroos and dingoes for bounty was both encouraged and rewarded under the *Act to Encourage the Destruction of Marsupials and Dingoes 1905* (5 Edw VII, No 8). In 1921, the *Animals and Birds Act* (12 Geo V, No 20) was passed in which, for the first time, protection was provided for all wildlife. Critically, this act also provided that every reserve existing at the commencement of the Act be constituted as a wildlife sanctuary where killing any animals is unlawful. Not long after, the *Native Plants Protection Act of 1930* (21 Geo 5 No 41) was passed. Under this Act, the Governor in Council had the power to proclaim a native plant protected under the Act and provide notice of its protection in a published Gazette notice. This provided penalties for harvesting or selling declared plants (s 2, 5).

In 1937, the Animals and Birds Act was replaced with the *Fauna Protection Act* (1 Geo VI, No 22). Under both Acts, the taking or killing of animals in sanctuaries was prohibited. Managing native animals on private land, however, varied slightly between the two Acts. Previously a landowner or his employees could kill native animals or birds to protect crops and orchards. The new Act restricted this by requiring landholders to request permission to cull after demonstrating sufficiently large populations and damage to crops (s 24). It was under the *Fauna Protection Act* that kolas (called native bears) were declared protected by an indefinitely closed harvesting season (s 8). Other natives (possums and kangaroos) could still be harvested during their declared open season which varied by species.

Formal restrictions on harvesting and hunting native species changed again in 1952 when the *Fauna Conservation Act* (1 Eliz II, No 13) was passed. This Act declared two classifications for native species: permanently protected and protected fauna. It placed restrictions or prohibitions on fauna harvesting based on their classification. Under this Act, no permanently protected fauna (e.g. echidnas, platypus, and koalas) and could be harvested. Protected fauna, which included everything else, could be only harvested during the open season specific to the species (s 19). This Act interacted with the above mentioned SFNP by declaring all land which is declared as

State Forest or National Park under the SFNP to be a "*sanctuary." The Fauna Conservation Act* was replaced once more in 1974 (1 Eliz, No 44, hereafter called the Fauna Act). This new Act retained most of the same powers regarding native species protection but added a new type of protected area. In Division II, power was given to the Governor in Council to create refuges for fauna (s 36) on private land which are now called "nature refuges."

Subordinate legislation

To achieve the objectives of the Nature Conservation Act, there are has seven pieces of subordinate legislation (Regulations). Two of these regulations apply to protected areas: the *Nature Conservation (Protected Areas) Regulation 1994 and the Nature Conservation (Protected Areas Management) Regulation 2006, (*hereafter, the PA Regulation and PA Management Regulation, respectively). The PA Regulation lists the formally dedicated protected areas and their location (*ie* the property boundary as per its lot on plan identification). If an area is not listed in the PA Regulation, it is not formally a protected area. The PA Management Regulation also outlines which types of activities can occur in protected areas (*ie* mountain biking or hiking). The PA Management Regulation interacts specifically with the Nature Conservation (Administration) Regulation 2017 (hereafter, Administration Regulation). The Administration Regulation provides a system of permits or other authorities to use in protected areas as well as detailed procedures and requirements for materials seized under the PA Management Regulation (The State of Queensland 2017).

More details on environmental impact assessments

Where a development fails to comply with guidelines associated with relevant Acts, an environmental impact assessment (EIA) may be required process by the appropriate authority (or division of Government). An EIS is also necessary for all "coordinated projects." A coordinated project is triggered by the *State Development and Public Works Organisation Act 1971 (SDPWO).* It refers to projects that are "strategically significant to the locality, region or State, require complex local, state or Commonwealth approval, or have significant positive or negative impacts on the infrastructure, social or physical environments or the economy (Queensland Government 2019b)." At the local government level, developments can require an EIS if one is required by the council's planning scheme (England 2016). Following an assessment of biodiversity assets in the proposed area, the regulatory authority (a unit or division of Government) will use their discretionary power (Zhang, Kørnøv, and Christensen 2018) to examine if the project is: i) unacceptable, ii) acceptable with conditions; iii) acceptable with no conditions or; iv) if an offset will be required.

An offset is a compensation mechanism for unavoidable impacts on environmental features. An offset can be similar land purchased in another location to be managed for biodiversity retention purposes, a financial settlement paid or a combination of these. Offsets, therefore, allow proponents to develop areas declared as MNES or MSES provided their application to do so is permitted. Despite the increasing popularity of offsets (Gordon et al. 2015), some studies suggest that they are inappropriate to achieve their desired outcomes or, by forcing an assumption of no change or "no net loss", offsets may exacerbate species decline where there is already a negative trajectory for species and habitats (Gibbons et al. 2016, Gordon et al. 2015). As reported by the Queensland offset register, over 15,000 hectares of significant environmental matters have been offset for development. This includes marine plants, high ecological significance wetlands, protected plants and assessable vegetation communities. While the offset policy was designed the marry the objectives ecologically sustainable development and conservation, researchers have questioned whether the exchanges are truly like-for-like and whether financial offsets provide measurable benefits for biodiversity. For this project, further research into environmental offsets is out of scope.

A1.3 Gazette Notices in support of Queensland's first national parks

It is widely reported that Witches Falls became Queensland's first national park in 1908 (Frost 2004, Sattler 1993). Representatives at the Department of Environment and Science responsible for maintaining geospatial data on Queensland's protected areas are also responsible for maintaining historical records for protected areas. In discussing Witches Falls with these officers, I learned that Barron Falls in North Queensland was actually declared a National Park before Witches Falls, and support for this claim is given in the form of a gazette notice (**Figure A2-1**). The gazette notice contains information about proclamations and announcements of the Commonwealth government. They are published by government departments or by private individuals when they are required by the Australian Government (Australian Government 2020a).

No. 85. Vol. LXXIV.] 748 [22nd September, 1900.

THE ROCKHAMPTON LAND AGENT'S DISTRICT.

Agricultural Farm—Annual rent, 3d. per acre.
Purchasing price, 10s per acre
Agricultural Homestead—Maximum area, 640 acres.
Annual rent, 3d. per acre.
Unconditional Selection—Annual rent, 8d. per acre.
Purchasing price, 13s. 4d. per acre.
(On forfeited O.L.'s 69 and 148.)

County of Pakington, parish of Windah.

Area, about 640 acres.

The Crown lands within the following boundaries:—

Commencing at the south-east corner of portion 1857, and bounded thence on the south by a line east about forty chains; on the east by a line north about one hundred and fifty chains; on the north by a line west to the Fitzroy River; on the west by that river upwards to portion 1711, by that portion and portion 1857 to the point of commencement;—exclusive of all lands required for roads, reserves, or other public purpose.

N.B.—Each selection will be subject to payment of the value of improvements, if any.

A PROCLAMATION.

By His Excellency The Right Honourable Charles Wallace Alexander Napier, Baron Lamington of Lamington, in the county of Lanark, in the Peerage of the United Kingdom, Knight Grand Cross of the Most Distinguished Order of St. Michael and St. George, Governor and Commander-in-Chief of the Colony of Queensland and its Dependencies.

[L.S.]
Lamington,
Governor.

In pursuance of the powers and authorities in me vested, and in accordance with the provisions of the 75th section of "*The Land Act*, 1897," I, Charles Wallace Alexander Napier, Baron Lamington, the Governor aforesaid, by and with the advice of the Executive Council, do, by this my Proclamation, notify and declare that the unselected Lands described in the accompanying Schedule shall be and are hereby withdrawn from selection.
E.M—19-9-00. 00-23542—L.B.

Given under my Hand and Seal, at Government House, Brisbane, this nineteenth day of September, in the year of our Lord one thousand nine hundred, and in the sixty-fourth year of Her Majesty's reign.

By Command, W. B. O'CONNELL.

God Save the Queen!

THE SCHEDULE.

Land Agent's District.	No. of Portion.	Parish.	Date of Proclamation.	Reference.
Gympie ...	10v	Imbil	1898. 2nd Mar.	A.H. 1551
Ditto ...	13v	ditto	ditto	ditto

A PROCLAMATION.

By His Excellency The Right Honourable Charles Wallace Alexander Napier, Baron Lamington of Lamington, in the county of Lanark, in the Peerage of the United Kingdom, Knight Grand Cross of the Most Distinguished Order of St. Michael and St. George, Governor and Commander-in-Chief of the Colony of Queensland and its Dependencies.

[L.S.]
Lamington,
Governor.

In pursuance of the powers and authorities in me vested under the provisions of sections 19 and 190 of "*The Land Act*, 1897," I, Charles Wallace Alexander Napier, Baron Lamington, the Governor aforesaid, by and with the advice of the Executive Council, do, by this my Proclamation, notify and declare that the land here-under described has been temporarily reserved for a Rifle Range.
E.M. 19-9-00.

THE CHARLEVILLE LAND AGENT'S DISTRICT.

Reserve for Rifle Range, Charleville.

00-24959—S.G.

County of Orrery, parish of Charleville.—Area, about 360 acres.

Commencing at a point bearing 90 degrees 6 minutes and distant two chains from the north-east corner of portion 97v, parish of Glengarry, and bounded thence on the north by a road bearing 90 degrees 6 minutes forty-one chains and nineteen links; on the east by a line bearing south about sixty-two chains and fifty links to the telegraph line; on the south-east by the telegraph line bearing 212 degrees 30 minutes about eighty-four chains to a peg; thence by the main Adavale road bearing north-westerly about five chains; and on the west by a road two chains wide along the east boundaries of portions 2, 1, and 97v, parish of Glengarry, about one hundred and thirty-four chains and ten links to the point of commencement;—as shown on plan deposited in the Surveyor-General's Office—Cat. No. O 53-127.

Given under my Hand and Seal, at Government House, Brisbane, this nineteenth day of September, in the year of our Lord one thousand nine hundred, and in the sixty-fourth year of Her Majesty's reign.

A PROCLAMATION.

By His Excellency The Right Honourable Charles Wallace Alexander Napier, Baron Lamington of Lamington, in the county of Lanark, in the Peerage of the United Kingdom, Knight Grand Cross of the Most Distinguished Order of St. Michael and St. George, Governor and Commander-in-Chief of the Colony of Queensland and its Dependencies.

[L.S.]
Lamington,
Governor.

In pursuance of the powers and authorities in me vested under the provisions of sections 19 and 190 of "*The Land Act*, 1897," I, Charles Wallace Alexander Napier, Baron Lamington, the Governor aforesaid, by and with the advice of the Executive Council, do, by this my Proclamation, notify and declare that the lands hereunder described have been temporarily reserved for the purpose named with respect to each.
E.M 19-9-00.

THE BUNDABERG LAND AGENT'S DISTRICT.

Reserve for Fire Brigade.

00-17205—Bund.

County of Cook, town and parish of Bundaberg, allotment 10 *of section* 10.

Area, 18 perches.

Commencing in Bourbong street at the north corner of allotment 9, and bounded thence on the north-west by Bourbong street bearing 65 degrees fifty links; on the north-east by allotment 4 bearing 155 degrees two chains and twenty-five links; on the south-east by a lane bearing 245 degrees fifty links; and on the south-west by allotment 9 bearing 335 degrees two chains and twenty-five links to the point of commencement;—as shown on plan of survey deposited in the Surveyor-General's Office—Cat. No. B158-42.

THE CAIRNS LAND AGENT'S DISTRICT.

Reserve for National Park, Barron Falls.

00-21182—S.G.

County of Nares, parishes of Cairns and Smithfield.

Area, about 7,500 acres.

Commencing on the left bank of the Barron River at the south-west corner of portion 7v, parish of Smithfield, and bounded thence on the north by that portion bearing east about 29 chains; on the east by a road and portion 132v bearing south 51 chains; again on the north by that portion bearing east 6 chains, 115 degrees 27 minutes 8 chains and 95 links, and by that portion and portion 133v bearing east 38 chains and 25 links; on the north-east by a line bearing about 105 degrees about 140 chains to the north-west corner of portion 226; on the east by that portion and portion 203 bearing south 100 chains and 58 links, and by a line in continuation crossing the Barron River to its right bank; thence by the right bank of the river downwards to portion 352; thence by that portion bearing west 25 chains and 14 links, 214 degrees 14 minutes 3 chains and 56 links, south 30 chains and 66½ links, and east 30 chains and 61 links; thence by a line bearing south to and across the railway line; thence by the railway line south-easterly to the intersection of the west boundary of portion 155; again on the east by that portion bearing south, by portion 321 bearing west and south, and by portion 137 bearing south to the south-west corner of the last-mentioned portion; on the south by a line bearing west about 70 chains; on the west and again on the south by lines bearing north about 130 chains and west about 240 chains; again on the west by a road along the east boundaries of portions 42v, 44v, 43v, 41v, 40v, 8v, 7v, 6v, and 5v bearing north and north-easterly to a point west of starting point; and thence by a line bearing east crossing the Barron River to the point of commencement;—exclusive of the Railway Reservation, of a Railway Reserve proclaimed in *Government Gazette*, 1891, part 3, page 204, of a Reserve for Extension of State Nursery, and of all alienated or surveyed lands within these described boundaries, as shown on plan deposited in the Surveyor-General's Office—Cat. No. N 157-199.

THE GYMPIE LAND AGENT'S DISTRICT.

Reserve for State Forest.

00-14825—Gym.

County of Lennox, parish of Widgee, portion 1491.—Area, 5,198 acres.

Commencing at the north-east corner of portion 811, and bounded thence on the north by portions 6 and 11 bearing east eighty-nine chains and four links to a road; thence by that road bearing easterly to the north-west corner of portion 1075; on the east by portions 1075, 942, 501, 193, 937, 1217, 192, 1228, 1172, and 1240; on the south by a line bearing west 172 chains and 25 links; and on the west by portion 811 bearing north 285 chains and 28 links to the point of commencement;—Cat. No. L 37-859.

Reserve for Timber.

00-16782—Gym.

County of Lennox, parish of Cambroon.—Area, 8,500 acres.

Commencing on the left bank of the Mary River at the north-east corner of portion 840, and bounded thence on the south by that portion and a line bearing west about 400 chains; on the west by a line bearing north about 240 chains to Little Yabba Creek; thence by the right bank of that creek downwards to portion 12, by that portion bearing south and east and by portion 11 bearing south and east to the Mary River; and thence by the left bank of that river upwards to the point of commencement;—as shown on plan deposited in the Surveyor-General's Office—Cat. No. L37-480.

THE NANANGO LAND AGENT'S DISTRICT.

Reserve for Water.

00-15634—Ngo.

County of Fitzroy, parish of Booie.—Area, about 7 acres.

Commencing at the north-east corner of portion 55v, and bounded thence on the south by that portion bearing west fourteen chains and fifty-one links; on the south-west by that portion and a line bearing 315 degrees five chains and forty-one and a-half links; on the north by portion 48v bearing east twenty-two chains and seventeen links; and on the south-east by a line and portion 39v bearing 225 degrees five chains and forty-one and a-half links to the point of commencement;—as shown on plan of survey deposited in the Surveyor-General's Office—Cat. No. Ftz. 37-165.

Given under my Hand and Seal, at Government House, Brisbane, this nineteenth day of September, in the year of our Lord one thousand nine hundred, and in the sixty-fourth year of Her

FigureA2-1: A gazette notice from 1900 declaring Barron Fall a National Park.

1883 . 1 . 1157

1157

boundaries of portions 1323, 985, 1078, 1070, 3, and 1069, to a point on the east boundary of 1069 two miles north from its south-east corner; thence by a line east two and a-quarter miles; thence by a line south about four and a-quarter miles to a point bearing south east from the south-east corner of portion 1069; thence by a line south-east to Munro Creek; thence by a line south-west six miles; thence by a line north-westerly to the range forming the watershed between Dadamarine Creek and Teebar Creek; by that range northerly to a point west from the north-west corner of selection 1361, parish of Boompa; thence by a line east to that north-west corner; thence by that selection south to Eel Creek; by that creek downwards to the south-east corner of selection 1361; thence by a line south to Sandy Creek; and by that creek upwards to the point of commencement.

RESERVE FOR TIMBER ON FRASER'S ISLAND.

1 square mile.

Commencing at a stake bearing north 129 degrees 30 minutes east from the eastern corner of Bowarrady No. 1 original boundary, and bounded thence by a line east thirty-seven chains; thence north 115 degrees east 2,150 links; thence north 25 degrees east seven chains; thence east again 3,950 links; thence south sixty-four chains; thence west 100 chains; and thence north sixty-four chains to the point of commencement.

RESERVE FOR TIMBER ON MYRTLE CREEK.

County of Lennox, parishes of St. Mary, Woocoo, and Gungalloon.

About 42 square miles.

Commencing at the south-east corner of portion 94, parish of St Mary, and bounded thence by a line bearing south forty chains; on the south by a line bearing west eight miles; on the west by a line bearing north to the road from Clifton Station to Maryborough; on the north by that road easterly to the west boundary of the timber reserve proclaimed in *Government Gazette* of 1875, folio 1300; on the east by that reserve bearing south to Myrtle Creek; thence by that creek downwards to the north-west corner of portion 95; and thence by the west and south boundaries of portions 95 and 94 southerly and easterly to the point of commencement,—exclusive of portions 96, 100, 1, 1,443, and a reserve.

RESERVE FOR TIMBER, AT MOUNT URAH.

County of Lennox, parish of Glenbar.

About 5,000 acres.

Commencing at the south-east corner of portion 808, selection 1022A; and bounded thence on the south by a line bearing east to the west boundary of selection 1362; thence by the west, north, and east boundaries of that selection bearing north, east, and south; and by a line south to the north boundary of selection 1356; thence by the north boundary of that selection bearing east to its north-east corner; on the east by a line bearing north passing along the west boundary of portion 475 about three and a-quarter miles to a point east from the north-east corner of the timber reserve proclaimed in *Government Gazette* for 1877, folio 806; on the north by a line bearing west to that north-east corner; and on the west by the timber reserve and selection 1022A southerly to the point of commencement.

RESERVE FOR RAILWAY PURPOSES.

Near the Burdekin crossing of the Charters Towers Railway, county of Davenport.

160 acres.

Commencing at a point bearing 205 degrees and distant 104 chains and fifty links from the north-east corner of the camping reserve proclaimed in the *Government Gazette* for 1878, vol. 2, folio 917, and bounded thence on the east by a line bearing 173 degrees 14 minutes forty chains; on the south by a line bearing 263 degrees 14 minutes forty chains; on the west by a line bearing 353 degrees 14 minutes forty chains; and on the north by a line bearing 83 degrees 14 minutes forty chains to the point of commencement.

RESERVE FOR TIMBER.

On the Barron River, county of Nares.

About 41 square miles.

Commencing on the main road from Herberton to Cairns at the 16-mile tree near Peterson's old camp, and bounded thence by a line northerly to the Barron River; thence by that river downwards to Tinaroo Creek at old Tinaroo; thence by a line easterly to the Herberton and Cairns road where it crosses the range forming the western watershed of the Mulgrave River; and thence by that road south-westerly to the point of commencement.

RESERVE FOR CAMPING ON COOPER'S CREEK, GREGORY SOUTH DISTRICT.

Resumed from the Galway Downs No. 3 and Hammond Downs West Runs.

Area, 6¼ square miles.

Commencing on the right bank of Cooper's Creek at a point opposite a tree marked broad-arrow in triangle, and bounded thence on the south by a west line along part of the north boundary of the Murken Run one mile fifty-eight chains; thence on the west by a north line two miles; thence on the north by an east line crossing Cooper's Creek at a point about fifty-six chains below a tree marked broad-arrow over C over 15 in triangle three miles fifty-six chains; thence on the east by a south line one mile seventy-two chains; and thence again on the south by a west line one mile sixty chains to Cooper's Creek at a tree marked broad-arrow in triangle; and thence by a line across the creek to the point of commencement.

Given under my Hand and Seal, at Government House, Brisbane, this twenty-sixth day of April, in the year of our Lord one thousand eight hundred and eighty-three, and in the forty-sixth year of Her Majesty's reign.

By Command,

P. PERKINS.

GOD SAVE THE QUEEN!

PROCLAMATION.

By His Excellency Sir ARTHUR EDWARD KENNEDY, Knight Grand Cross of the Most Distinguished Order of St. Michael and St. George, Companion of the Most Honourable Order of the Bath, Governor and Commander-in-Chief of the Colony of Queensland and its Dependencies.

[L.S.]
A. E. KENNEDY,
Governor.

IN pursuance of the provisions of "*The Crown Lands Alienation Act of 1876*," I, Sir ARTHUR EDWARD KENNEDY, the Governor aforesaid, with the advice of the Executive Council, do, by this my Proclamation, notify and proclaim that the lands hereunder described, having been resumed under the provisions of "*The Western Railway Act*," shall be open to Selection, under the provisions of the first-mentioned Act, on and after TUESDAY, 15th May, 1883, at Miles.

And I further notify and proclaim that the upset price at which the said lands are open to selection by Conditional Purchase shall be ten shillings per acre, and that the area which may be selected by Conditional Purchase shall not exceed 5,120 acres.

ROMA LAND AGENT'S DISTRICT.

Lands resumed from Wallan No. 2 Run, Unsettled District of Darling Downs.

About 67,000 acres.

Commencing on Wallan Creek at the south-east corner of Wallan No. 1 Run, and bounded thence on the west by a line bearing north to L-tree Creek; on the north by that creek downwards to Bottle-tree Creek; on the east by that creek and Dogwood Creek downwards to Wallan Creek; and on the south by Wallan Creek upwards to the point of commencement.

1883 . 1 . 1157

FigureA2-2: Gazette Notice Barron River Timber Reserves in 1883.

1882.2.885

885

PROCLAMATION.

By His Excellency Sir ARTHUR EDWARD KENNEDY Knight Grand Cross of the Most Distinguished Order of St. Michael and St. George, Companion of the Most Honourable Order of the Bath, Governor and Commander-in-Chief of the Colony of Queensland and its Dependencies.

[L.S.]
A. E. KENNEDY,
Governor.

IN pursuance of section six of "*The Crown Lands Alienation Act of* 1876," I, Sir ARTHUR EDWARD KENNEDY, the Governor aforesaid, with the advice of the Executive Council, do, by this my Proclamation, notify and proclaim that the lands hereunder described have been temporarily reserved for the purpose named with respect to each.

RESERVE FOR SHOW PURPOSES ON MOOYUMBIN CREEK.

County of Ward, parish and town of Nerang, portion No. 11A.

8 acres 3 roods 8 perches.

Commencing on the left bank of Mooyumbin Creek at the south-east corner of portion 11, and bounded thence on the west by that portion and portion 10 bearing north seven chains and forty-four links and passing through a post eight links from said creek; on the north by a road bearing east ten chains and forty-nine links; on the south-east by Martin street bearing 201 degrees 23 minutes twelve chains and sixty-five and a-half links; on the south-west by Tilbing street bearing 291 degrees 23 minutes five chains and thirty-nine and a-half links to Mooyumbin Creek, and passing through a post five links from said creek; and thence by that creek upwards to the point of commencement.

R3.

RESERVE FOR A STATE FOREST, ON FRASER ISLAND.

Commencing on the shores of Hervey's Bay at the mouth of Bogimba or Mitchell's Creek, and bounded thence by a line east to the shores of the Pacific Ocean; thence by the shore of the Pacific Ocean southerly about nineteen miles to a pandanus-tree marked broad-arrow over TR; thence by a line west 419 chains to a post bearing 26 degrees 10 minutes and distant forty-two links from a blackbutt-tree marked broad-arrow over TR; thence by a line bearing north ten chains crossing the source of Tumbowah or Yankee Jack's Creek to a tea-tree marked broad-arrow over TR; thence by the right bank of Tumbowah or Yankee Jack's Creek downwards to its outlet into Great Sandy Island Strait at a bloodwood-tree marked broad-arrow over TR; thence by the shores of Great Sandy Island Strait and Hervey's Bay to the point of commencement,—exclusive of alienated land and Quarantine Reserve.

RESERVE FOR ABORIGINALS, ON BAKER'S CREEK

County of Carlisle, parish of Chelona.

630 acres.

Commencing on the right bank of Baker's Creek at a point 325 links east from the north-east corner of portion 914, and bounded thence on the north by a line bearing west three chains and twenty-five links; on the west by portion 914 and a line bearing south 109 chains and ninety-seven links; on the south and west by portion 719 bearing east fifteen chains and thirty-one links and south thirty-eight chains; again on the south by portions 727 and 857 bearing east forty-eight chains and seventeen links; and on the east by lines bearing 22 degrees 55 minutes twenty-seven chains and thirty-three links, 332 degrees 24 minutes twenty-nine chains and fifty-four links, 350 degrees 30 minutes fifty-two chains to Baker's Creek; thence by that creek upwards to the point of commencement.

RESERVE FOR ROAD METAL.

County of Carlisle, parish of Bassett, portion 81A.

6 acres.

Commencing on a road at the north-east corner of portion 80A, and bounded thence on the north by that road bearing east six chains; on the east by portion 82A bearing south ten chains; on the south by portion 69A bearing west six chains; and on the west by portion 80A bearing north ten chains to the point of commencement.

RESERVE FOR A MANURE DEPOT, ON SALTWATER CREEK.

County of Elphinstone, parish of Coonambelah.

2 acres.

Commencing on the left bank of Saltwater Creek at a point bearing 180 degrees 22 minutes and distant 814 links from the south-east corner of the North Queensland Pastoral and Agricultural Society Reserve, and bounded thence on the east by a line bearing 22 minutes four chains and sixty links and passing through a post fourteen links from said creek; on the north by a line bearing west three chains and forty-five links; on the west by a line bearing 180 degrees 22 minutes four chains to Saltwater Creek and passing through a post twenty links from said creek; on the west by that creek downwards to selection 1A; on the south by that selection bearing 89 degrees 46 minutes 174 links to same creek; thence by the creek downwards to the point of commencement.

RESERVE FOR A SCHOOL OF ARTS.

County of Nares, parish and town of Cairns, allotments 9 *and* 10 *of section* 8.

2 roods.

Commencing at the west corner of allotment 8, section 8, and bounded thence on the north-east by Lake street bearing 135 degrees two chains; on the south-east by Shields street bearing 225 degrees two chains and fifty links; on the south-west by allotments 11 and 12 bearing 315 degrees two chains; and on the north-west by allotment 8 bearing 46 degrees two chains and fifty links to the point of commencement.

RESERVE FOR SCHOOL OF ARTS.

County of Davenport, parish and town of Millchester, allotment 5 *of section* 4.

$36\frac{3}{4}$ perches.

Commencing on the north-west side of Jardine street at the south corner of allotment 4, and bounded thence on the south-east by that street bearing 220 degrees ninety-two links; on the south-west by Hacket street bearing 310 degrees two chains and fifty links; on the north-west by a line bearing 40 degrees ninety-two links; and on the north-east by allotment 4 bearing 130 degrees two chains and fifty links to the point of commencement.

RESERVE FOR PUBLIC PURPOSES, ON THE MULGRAVE RIVER.

County of Nares, parish of Sophia.

About 3,000 acres.

Commencing on the sea-coast at Palmer Point, and bounded thence on the north by a line bearing west about one and a-half miles; on the west by a line bearing south about two and a-half miles; thence by a line bearing west about half-a-mile to the Mulgrave River; thence by that river downwards to the Pacific Ocean; and on the east by that ocean northerly to the point of commencement.

Also,

County of Nares, parish of Russell.

About 2,000 acres.

Commencing on the sea-coast at a point about sixty chains southerly from Bramston Point, and bounded thence on the south-east by a line bearing 225 degrees about one mile; on the south-west by a line bearing 315 degrees about 190 chains; thence by a line bearing west to the Russell River; thence by that river downwards to its confluence with the Mulgrave River; on the north by that river downwards to the Pacific Ocean; and thence by that ocean southerly to the point of commencement.

Given under my Hand and Seal, at Government House, Brisbane, this thirtieth day of September, in the year of our Lord one thousand eight hundred and eighty-two, and in the forty-sixth year of Her Majesty's reign.

By Command,

P. PERKINS.

GOD SAVE THE QUEEN!

FigureA2-3: Gazette Notice State Forest on Fraser Island 1882.

A1.4 Queensland's bioregions and National Reserve System reporting

Queensland is home to a wide variety of ecosystems including grasslands, deserts, wetlands, woodlands and tropical rainforests. To represent this diversity, Queensland is divided into 13 bioregions. Bioregions demarcate distinct areas based on climate, geology and biota (Thackway and Cresswell 1997) and are the reporting unit for assessing the extent of protection of ecosystems in Australia's National Reserve System (Environment Australia 2000). For example, Australia's obligations under the International Convention on Biological Diversity requires that at least 12 per cent of land is conserved through an ecologically representative and well-connected reserve system (UNEP 2011), but Australia has not met that target (Williams, Harwood, and Ferrier 2016). Furthermore, there are no bioregions in Queensland which contain all nine types of protected areas, and, owing to complex land-use across bioregions, the distribution of protected area tenures across bioregions are unequal. For example, the Brigalow Belt has few National Parks and more State forests than other Region, and the majority of conservation areas on the Cape York Peninsula are Aboriginal National Parks (also called Indigenous Protected Areas, IPAs) (2.1m ha). Despite the enormous value of Aboriginal National Parks for securing biodiversity heritage values, a key challenge for IPAs is the limited and uncertain financial resourcing from the Australian Government's IPA program (Grace 2016). Insecure funding means that these areas are not secured to perpetuity, and their status as cultural heritage areas could be lost. Differences in the representation of different protected area classes have implications for evaluating their effectiveness.

While bioregions demarcate distinct areas based on climate, geology and biota (Thackway & Cresswell 1997), they are also and are the reporting unit for assessing the extent of protection of ecosystems in Australia's National Reserve System (Environment Australia 2000). In addition to ecological differences, there are obvious distinctions in the type and extent of protected areas per bioregion. Thus, unlike previous studies which consider broad-scale regions such as States or Territories, I analyse separate bioregions to avoid misleading comparisons across ecologically dissimilar areas while also providing a comprehensive, State-wide perspective.

Appendix 2: Supporting information for Chapter 2

A2.1 Substantive documents included in analysis

TableA2-1: Title of the substantive documents used in Chapter 2's policy analysis. Data are organised by jurisdiction and attributed with the year in which they were published.

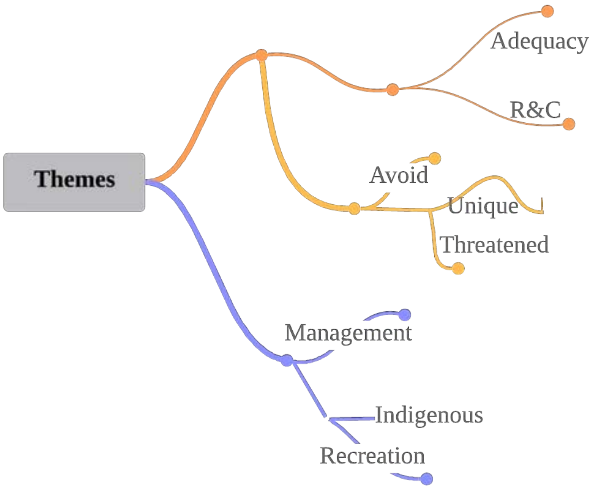
Policy Title	*Year*
Federal	
An interim biogeographic regionalisation for Australia	1995
Australia's Strategy for the National Reserve System	2009
Australian Guidelines for Establishing the National Reserve System	1999
Australia's Biodiversity Conservation Strategy 2010-2030	2010
Australia's strategy for nature	2018
Directions for the National Reserve System: A partnership approach	2005
National Forest Conservation Reserves: Commonwealth Proposed Criteria	1995
National Forest Policy Statement	1992
National Objectives and targets for biodiversity conservation	2001
National Strategy for the Conservation of Australia's Biological Diversity	1996
Nationally Agreed Criteria for the Establishment of a Comprehensive, Adequate and Representative Reserve System for Forests in Australia	1997
Australian Capital Territory (ACT)	
ACT Nature Conservation Strategy 2013-2023	2013
Canberra Spatial Plan	2007
New South Wales (NSW)	
A new Biodiversity Strategy for New South Wales	2010
Biodiversity: life's variety NSW Biodiversity Strategy	1999
Draft Biodiversity Conservation Investment Strategy 2017-2037 A strategy to guide investment in private land conservation	2017
Draft New South Wales Biodiversity Strategy 2010–2015	2010
New South Wales National Parks Establishment Plan 2008 Directions for building a diverse and resilient system of parks and reserves under the National Parks and Wildlife Act	2008
Northern Territory (NT)	
Northern Territory Parks and Conservation Masterplan	2005
Territory 2030 Strategic Plan	2009
Territory Eco-link: large framework, small budget	2012
Queensland (Qld)	
A Master Plan for Queensland's Parks and Forests	2015
Building nature's resilience	2010
Conserving natural and cultural heritage	2012
Draft Protected Area Strategy	2016
South Australia	
Conserving Nature Government of South Australia A strategy for establishing a system of protected areas in South Australia	2012
Draft Strategic Plan (2018 – 2028)	2017

Policy Title	*Year*
No Species Loss: Overview for South Australia 2007–2017 Government of South Australia A Nature Conservation Strategy	2013
South Australia's Nature Links Program: Successfully Integrating Protected Areas into Landscape Scale Conservation	2013

Policy Title	Year
Tasmania	
Natural Heritage Strategy for Tasmania	2013
Tasmania's Nature Conservation Strategy 2002 - 2006	2002
Victoria	
Criteria and Indicators for Sustainable Forest Management in Victoria Guidance Document	2007
Protecting Victoria's Environment - Biodiversity 2037	2017
Western Australia	
100-year Biodiversity Conservation Strategy for Western Australia: Blueprint to the Bicentenary in 2029	2007
Department of Parks and Wildlife Strategic Directions 2014-2017	2013
Establishment of a Comprehensive, Adequate and Representative Terrestrial Conservation Reserve System in Western Australia	2013
Forest management plan 2014-2023	2013
Hope for the future: the Western Australian State of Sustainability	2003
Kimberly Science Conservation Strategy	2011
Plan for our Parks	2019
Strategic Directions 2014-2017	2013

A2.2 Theme similarity

I used a Jaccard Similarity Index to compare word similarity between major themes and represented this similarity with a horizontal dendrogram(Niwattanakul et al. 2013). The Jaccard Index is a coefficient of similarity proportional to the number of common words in each theme (Sheth 2013, Castano, Ferrara, and Montanelli 2017). I found that the themes were divided into three main branches: i) indigenous values, social values and management ; ii) adequacy and R&C; and iii) avoiding loss, threatened species and communities and iconic or unique species or communities. Management, Indigenous values and recreation tended to use similar language. Avoiding threatening processes, unique areas or species and threatened ecosystems or species were a separate cluster, but this cluster used phrasing that was similar to adequacy and R&C. **(Figure A2-4)**.



FigureA2- 4: Priority themes clustered by word similarity. Themes that are closer to each other in the branches are more similar and themes that are further from each other are less similar.

A2.3 Progress against the most common theme

Representativeness and comprehensiveness is the most common strategic priority discussed at a State, Territory and Federal level. Progress against this target is also one of the simplest to measure as one indicator of representativeness, vegetation communities, is made freely available by the Australian Government (Deparment of the Environment. 2018). I assessed how well vegetation types in Australia are represented in protected areas. I found that the most highly represented vegetation types were cool, temperate rainforests (NVIS category 1; 65%), Eucalyptus low open woodlands with hummock grasses (NVIS category 18; 63.21%) and Eucalyptus open forests with a shrubby understory (NVIS category 4, 60.17%). The least represented vegetation communities were Eucalyptus woodlands with a tussock grass understory (NVIS category 9; 7.42%), Tropical Eucalyptus open forests and woodlands with a tall annual grassy understory (NVIS category 7; 8.96) and Tropical mixed-species forests and woodlands (NVIS category 11; 11.69%) **(Figure A2-1).** Due to Australia's complex evolutionary history and high climatic variability, vegetation communities are not uniformly distributed across States.

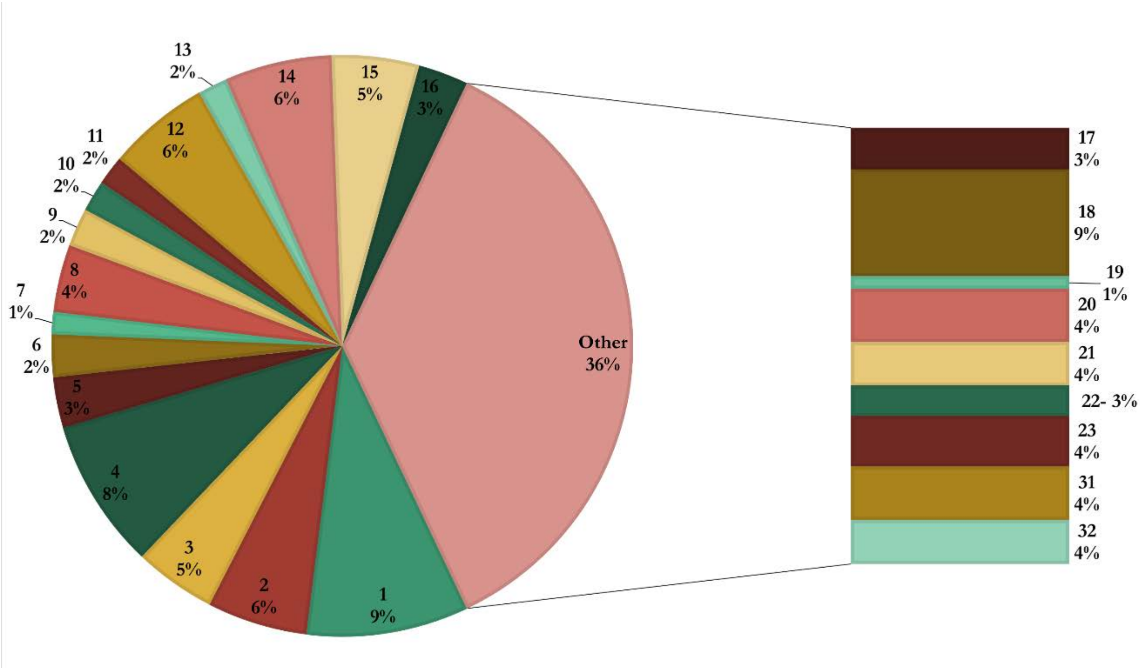


Figure A2-1 Proportional representation of each NVIS category in Protected Areas. NVIS categories 24-30 & 99 are classified as "other vegetation categories" and are excluded from this figure. 1: Rainforests and Vine Thickets, 2 Eucalypt Tall Open Forests3 Eucalypt Open Forests, 4 Eucalypt Low Open Forests,5 Eucalypt Woodlands, 6 Acacia Forests and Woodlands 7 Callitris Forests and Woodlands,8 Casuarina Forests and Woodlands, 9 Melaleuca Forests and Woodlands, 10 Other Forests and Woodlands, 11 Eucalypt Open Woodlands 12 Tropical Eucalypt Woodlands/Grasslands, 13 Acacia Open Woodlands, 14 Mallee Woodlands and Shrublands, 15 Low Closed Forests and Tall Closed Shrublands, 16 Acacia Shrublands, 17 Other Shrublands, 18 Heathlands 19 Tussock Grasslands 20 Hummock Grasslands, 21 Other Grasslands, Herblands, Sedgelands and Rushlands, 22 Chenopod Shrublands, Samphire Shrublands and Forblands 23 Mangroves, 24 Inland Aquatic - freshwater, salt lakes, lagoons, 25 Cleared, Non-Native Vegetation, Buildings, 26 Unclassified Native Vegetation, 27 Naturally Bare - sand, rock, claypan, mudflat, 28 Sea and Estuaries, 29 Regrowth, Modified Native Vegetation 30 Unclassified Forest 31 Other Open Woodlands, 32 Mallee Open Woodlands and Sparse Mallee Shrublands, 99 Unknown/No Data.

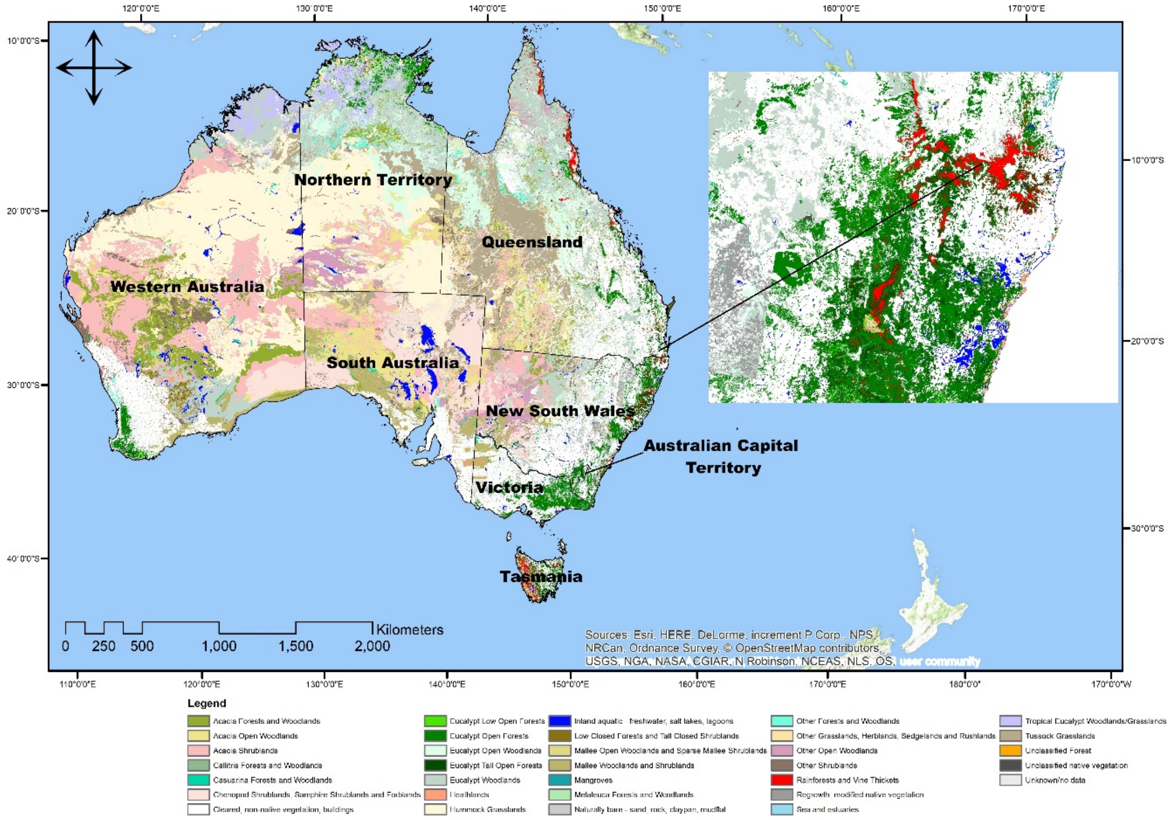


Figure A2-2: Distribution of major vegetation groups (MVGs) in each Australian State or Territory. The data presented here are freely available from the Australian Government's Spatial data portal (https://data.gov.au/data/)

Table A2-2: Major Vegetation Groups of the National Vegetation Information System (NVIS). (NVIS Technical Working Group 2017) The category refers to the numeric classification within the dataset and corresponds to its description. The total area and percent of the total NVIS category area within protected areas (Pct_Pas) was calculated in ArcMap 10.7 using the projected coordinate system MGA 94. Protected areas in this context refer to Collaborative Australian Protected Area Database (CAPAD (Australian Government 2019)). All data are publicly available and were sourced from: https://data.gov.au/data/. The final columns are named as per the abbreviations for each State and Territory and refer to proportion of the total amount of each NVIS category in each of the states or territories.

Category	*Description*	*Total area (ha)*	*Pct_PA*	*ACT*	*NSW*	*NT*	*Qld*	*SA*	*Tas*	*Vi c*	*WA*
1	Rainforest and vine thicket	3599680	65.03%	0.00%	10.42	4.78%	34.10%	0.00%	15.19%	0.48%	0.00%
2	Eucalypt tall open forests	3551870	40.02%	0.00%	25.72	0.00%	2.90%	0.00%	8.48%	0.59%	2.32%
3	Eucalypt open forests	22690080	32.76%	0.37%	8.96	9.54%	4.25%	0.05%	1.03%	6.13%	2.41%
4	Eucalypt low open forest	1136480	60.17%	0.00%	6.58	37.22%	1.25%	0.05%	9.13%	0.00%	5.92%
5	Eucalypt woodlands	85313400	20.29%	0.03%	2.10	5.59%	4.71%	0.26%	0.48%	0.70%	6.40%
6	Acacia forests and woodlands	34053000	17.04%	0.00%	0.28	0.66%	1.67%	0.70%	0.00%	0.02%	13.71%
7	Callitris forests and woodlands	3410700	8.96%	0.00%	6.40	0.00%	0.83%	0.81%	0.01%	0.01%	0.90%
8	Casurina forests and woodlands	1616740	26.95%	0.05%	0.87	2.44%	1.92%	11.85%	0.00%	6.69%	3.03%
9	Melaleuca forests and woodlands	8108980	15.36%	0.00%	0.27	5.54%	7.97%	0.04%	0.09%	0.00%	1.45%
10	Other forests and woodlands	4457030	12.47%	0.00%	0.05	2.37%	4.64%	0.10%	1.42%	0.72%	3.17%
11	Eucalypt open woodlands	46380800	11.69%	0.00%	0.44	7.19%	3.26%	0.15%	0.00%	0.21%	0.43%
12	Tropical eucalypt woodlands and grasslands	13614200	41.08%	0.00%	0.00	13.18%	0.13%	0.00%	0.00%	0.00%	27.73%
13	Acacia Open Woodlands	38295000	11.73%	0.00%	0.24	0.32%	1.61%	7.64%	0.00%	0.00%	1.91%
14	Mallee woodlands and shrublands	21329800	42.93%	0.00%	2.18	0.08%	0.59%	26.86%	0.00%	5.25%	7.96%
15	Low closed forests and tall closed shrublands	1825910	34.91%	0.00%	0.02	0.00%	4.09%	0.03%	14.17%	0.53%	16.00%
16	Acacia shrublands	85522704	20.03%	0.00%	0.16	1.20%	0.68%	4.45%	0.00%	0.00%	13.52%

Category	*Description*	*Total area (ha)*	*Pct_PA*	*ACT*	*NSW*	*NT*	*Qld*	*SA*	*Tas*	*Vi c*	*WA*
17	Other shrublands	12223800	24.79%	0.00%	0.47	0.68%	2.48%	4.42%	0.39%	0.81%	15.51%
18	Healthlands	1565000	63.21%	0.00%	10.64	0.00%	6.19%	9.68%	16.28%	12.66%	7.66%
19	Tussock grasslands	52630900	7.42%	0.00%	0.52	1.12%	2.09%	2.17%	0.02%	0.01%	1.47%
20	Hummock grasslands	1.37E+08	31.60%	0	0.00	10.45%	1.06%	3.38%	0.00%	0.00%	16.72%
21	Other grasslands, herblands, sedgelands and rushlands	4796500	25.86%	0.000544	1.41	7.01%	3.42%	0.80%	9.47%	0.92%	2.74%
22	Chenopod shrublands, samphire shrublands and forblands	48925700	18.07%	0	0.44	1.00%	0.61%	14.00%	0.01%	0.12%	1.89%
23	Mangroves	1046820	29.88%	0	0.27	10.76%	8.85%	0.21%	0.00%	0.24%	8.44%
31	Other open woodlands	16948300	31.67%	0.00%	1.19	16.95%	2.82%	1.61%	0.10%	0.00%	8.99%
32	Mallee open woodlands and sparse mallee shrublands	2069110	25.89	0.00%	2.90	4.13%	0.09%	4.08%	0.00%	1.41%	13.27%
	Other cover types (developed areas)										

Appendix 3: Supporting information for Chapter 3

A3.1 Workflow

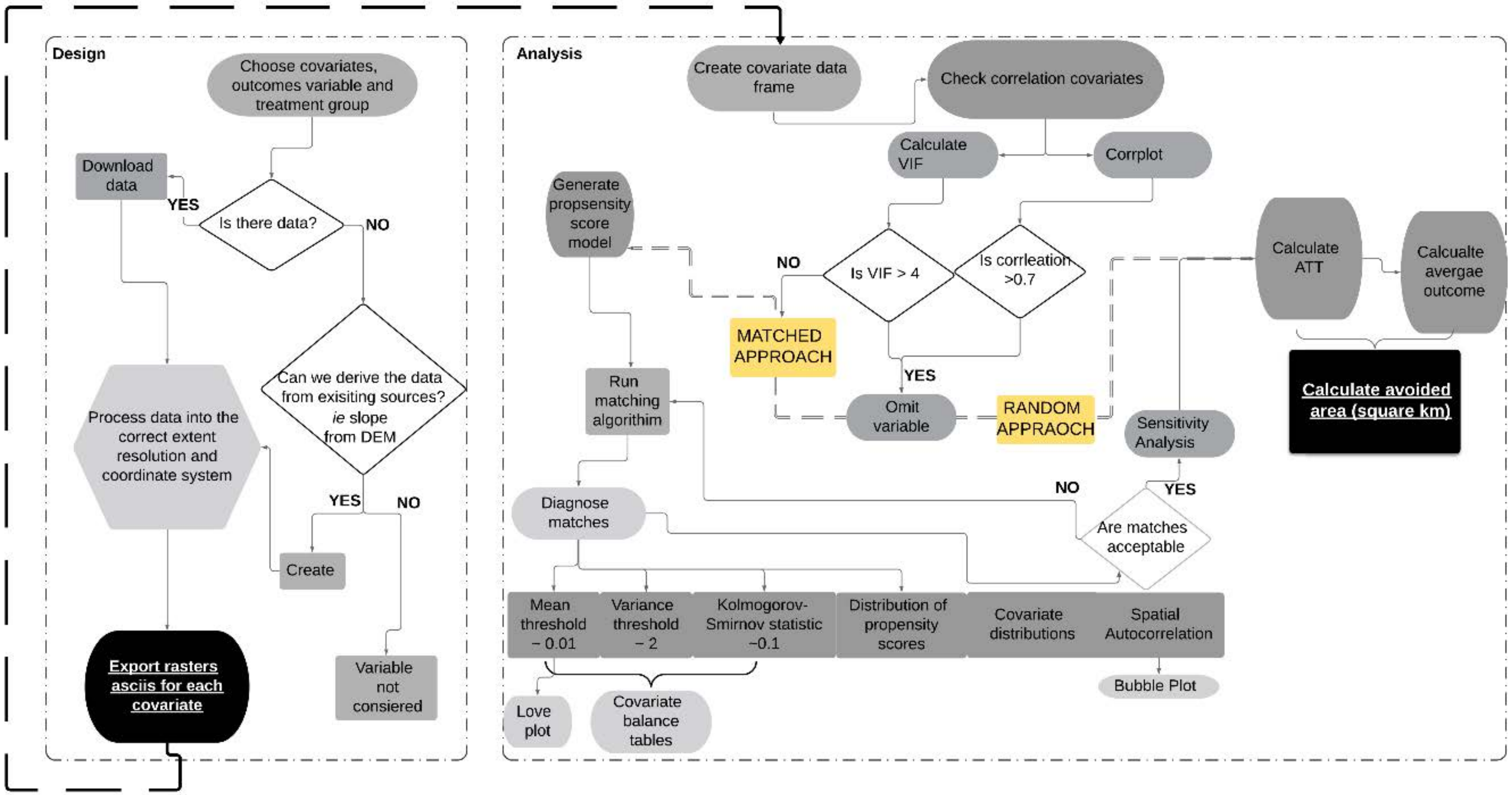


Figure A3- 1 Flow chart for the two methods stages in this analysis: design (left) and analysis (right). #This process was repeated for the random (unmatched sample).

Data processing

A failure to account for distinct ecological and biophysical characteristics by bioregions are classified may result in inappropriate matches. I analysed each bioregion separately by first creating an empty spatial grid for each bioregion. I then joined data from each co-variate, outcome variable and protected unit to a new dataframe based on the central coordinate of the grid for each bioregion. All co-variates listed in **Table 3-1** (main text) were rasterised with a snap raster of our base grid. This ensured all data were in the same extent, resolution (250m*250m) and coordinate system. (GCS GDA 1994, Zone 54)(Janssen 2009).

Combinations of substrate characteristics and vegetation type determine land suitability for production. Combinations of these characteristics are available in Queensland's comprehensive state-wide mapping of regional ecosystems (Sattler and Williams 1999). Their classification is a three-part code where the first part of the code defines the ecosystems biogeographic region. The second establishes the ecosystem's land zone (simplified geology and substrate), and the third defines the dominant vegetation (Wilson and Taylor 2012a). Landzones, therefore, provided the highest resolution and most comprehensive data geological data. I rasterised landzones in ArcMap 10.4.1 (Esri 2006) from regional ecosystem data version 10.1(Wilson, Neldner, and Accad 2002). Vegetation categories were rasterised from 6 vegetation groups (BVGs, 1:5m) (Neldner et al. 2014).

I sourced the following datasets from the Queensland Government's publicly available spatial database (Queensland Government 2019c): digital elevation model, grazing capacity, built-up areas, major watercourses, and state-controlled roads. Hillshade and Slope data were derived from a digital elevation model. I used a z-factor of 0.00000956 to calculate slope in per cent rise. Annual precipitation and temperature were calculated using ANUCLIM (Xu and Hutchinson 2011, Booth et al. 2014).

Deforestation

I rasterised deforestation data sets using the bioregion grid (section 2.1.1 of the main text) as snap raster. I gave each deforested pixel a value of "1" and joined the datasets together using raster calculator. We reclassified any pixels where clearing had occurred more than once as "1" and anything with missing values as"0" in ArcMap (ESRI 2014).

Protected areas

To accurately determine the declaration year for each protected area, I used spatial data from the Queensland Protected Area Spatial Data (Department of Environment and Science 2018), and hard-copy maps at a scale of 1:2 million. Hard-copy maps were available for the following time-steps: 1978, 1988, 1997, 2007. I used digital data for the most recent time step (2018). For each, we studied: the boundary of each park attributed a gazettal year to the whole protected area based on the time steps, then excluded entire protected areas declared before 1988. For example, protected areas that appeared on the 1988 map, but did not appear on the 1978 map were given the gazettal year of 1988. All areas declared before 1988 were excluded from further analysis. We created a "protected" layer by rasterising all the protected-area data using the aforementioned bioregion grids as snap rasters and reclassifying all areas under strict protection between 1988-2018 as"1" and all other areas as"0"

Categorical Variables

Broad vegetation groups (BVGs) and Landzones

Broad vegetation groups (BVGs) are high-level vegetation community grouping. While regional ecosystems classifications are nested within bioregions, BVGs are not and provide thus provide a useful overview of the distribution of vegetation across the state. **Table A3-1** provides a brief description of each BCG, and detailed descriptions of BVGs are provided in (Neldner, Niehus, et al. 2017). Across the State, there are thirty-five broad vegetation groups mapped at a 1:2M scale.

TableA3-1: Values associated with broad vegetation group general descriptions from (Neldner, Niehus, et al. 2017).

BVG	*General description*
1	Complex mesophyll to notophyll vine forests of the Wet Tropics bioregion
2	Complex to simple, semi-deciduous mesophyll to notophyll vine forests, sometimes with *Araucaria cunninghamii* (hoop pine)
3	Notophyll vine forests/ thickets (sometimes with sclerophyll and/or Araucarian emergents) on coastal dunes and sand masses
4	Notophyll and mesophyll vine forests with feather or fan palms on alluvia, along streamlines and in swamps on ranges or within coastal sand masses
5	Notophyll to microphyll vine forests, frequently with Araucaria spp. or Agathis spp. (kauri pines)
6	Notophyll vine forest and microphyll fern forests to thickets on high peaks and plateaus
7	Semi-evergreen to deciduous microphyll vine thickets
8	Wet eucalypt tall open forests on uplands and alluvia
9	Moist to dry open eucalypt forests to woodlands usually on coastal lowlands and ranges
10	*Corymbia citriodora* (spotted gum) dominated open forests to woodlands on undulating to hilly terrain
11	Moist to dry open eucalypt forests to woodlands mainly on basalt areas (land zone 8)
12	Dry eucalypt woodlands to open woodlands, mostly on shallow soils in hilly terrain (mainly on sandstone and weathered rocks, land zones 7 and 10)

BVG	*General description*
13	Dry to moist eucalypt woodlands and open forests, mainly on undulating to the hilly terrain of mainly metamorphic and acid igneous rocks, Land zones 11 and 12)
14	Woodlands and tall woodlands dominated by *Eucalyptus tetrodonta* (Darwin stringybark) (or *E.megasepala*), or *Corymbia nesophila* (Melville Island bloodwood) or *E. phoenicea* (scarlet gum)
15	Temperate eucalypt woodlands
16	Eucalyptus spp. dominated open forest and woodlands drainage lines and alluvial plains
17	*Eucalyptus populnea* (poplar box) or *E. melanophloia* (silver-leaved ironbark) (or *E. whitei* (White's ironbark)) dry woodlands to open woodlands on sandplains or depositional plains
18	Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains
19	Eucalyptus spp. (*E. leucophloia* (snappy gum), *E. leucophylla* (Cloncurry box), *E. persistens*, *E.normantonensis* (Normanton box)) low open woodlands often with Triodia spp. dominated ground layer
20	Callitris glaucophylla (white cypress pine) or C. intratropica (northern cypress pine) woodlands to open forests
21	Melaleuca spp. dry woodlands to open woodlands on sandplains or depositional plains
22	Melaleuca spp. open forests and woodlands on seasonally inundated lowland coastal swamps and fringing drainage lines (Palustrine wetlands)
23	Acacia aneura (mulga) woodlands to tall open shrublands on red earth plains, sandplains or residuals
24	*Acacia spp*. low woodlands to tall shrublands on residuals. Species include *A. clivicola*/ *A. sibirica* (bastard mulga), *A. shirleyi* (lancewood), *A. microsperma* (bowyakka), *A. catenulata* (bendee), *Acacia rhodoxylon* (rosewood)
25	*Acacia harpophylla* (brigalow) sometimes with *Casuarina cristata* (belah) open forests to woodlands on heavy clay soils
26	*Acacia cambagei* (gidgee) /*A. georginae* (Georgina gidgee) /*A. argyrodendron* (blackwood) open forests to tall shrublands
27	Mixed species woodlands to open woodlands (Atalaya hemiglauca (whitewood), Lysiphyllum spp., Acacia tephrina (boree), wooded downs
28	Open forests to open woodlands in coastal locations. Dominant species such as Casuarina spp., Corymbia spp., Allocasuarina spp. (she-oak), Acacia spp., Lophostemon suaveolens (swamp box), Asteromyrtus spp., Neofabricia myrtifolia
29	Heathlands and associated scrubs and shrublands on coastal dunefields and inland montane locations
30	Astrebla spp. (Mitchell grass), Dichanthium spp. (bluegrass) tussock grasslands
31	Mixed open forblands to open tussock grasslands in inland locations
32	Closed tussock grasslands in coastal locations

BVG	General description
33	Hummock grasslands dominated by Triodia spp. (spinifex) or Zygochloa paradoxa (sandhill canegrass) associations on dunefields or sandplains
34	Wetlands associated with permanent lakes and swamps, as well as ephemeral lakes, claypans and swamps. Includes fringing woodlands and shrublands
35	Mangroves and saltmarshes

Landzone

Landzones categories describe the general geology and associated landforms in Queensland. Landzones are categorised by the effects that geology has on geomorphology and soil formation **Table A5-1**. Sand dunes make up the largest areas in protection as a proportion of their total extent (Land Zone 2, 48%). The second most protected land zone is land zone 6, inland dunefields. The sediment found in these types of landzones is highly unfertile and suggests a bias towards less fertile land. (Figure 2). Further, land zone 9 is one of the largest landzones in the state and is described as having moderate to high fertility. This landzone, however, has only 5% of its total area represented in protected areas There is, therefore, non-random selection of broad vegetation groups and land zones, and inclusion of BVGs and land zones is, therefore, necessary BVGs and land zones were included as categorical covariates for this analysis.

TableA3- 2: Landzone definitions from (Wilson and Taylor 2012b).

Landzone	General description
1	Tidal flats and beaches
2	Coastal dunes
3	Alluvial river and creek flats
4	Clay plains
5	Old loamy and sandy plains
6	Inland dunefields
7	Cainozoic duricrusts
8	Cainozoic igneous rocks
9	Fine-grained sedimentary rocks
10	Sandstone ranges
11	Hills and lowlands on metamorphic rocks
12	Hills and lowlands on granite rocks

Model specification

To identify unacceptably high levels of correlation, I created correlograms (Supplementary Figures 2-6). Correlograms are graphs of correlation matrices that highlight the correlated co-variates of a data frame (Wei et al. 2017). For each bioregion, I considered deleting variables which exceeded a 0.7 threshold; however, previous studies have instructed modellers to retain ecologically reasonable variables (Dormann et al. 2013). Of the co-variates included in this study, the only rain and temperature in the Mulga Lands and roads and built-up areas in the Wet Tropics were significantly correlated. I excluded temperature from all bioregions because it consistently had a high variance inflation factor (VIF (Hair et al. 2013)). We, therefore, kept roads and built-up areas in the Wet Tropics because roads cross-section protected areas, allowing access. This is a significant socio-economic variable and deemed necessary for our analysis.

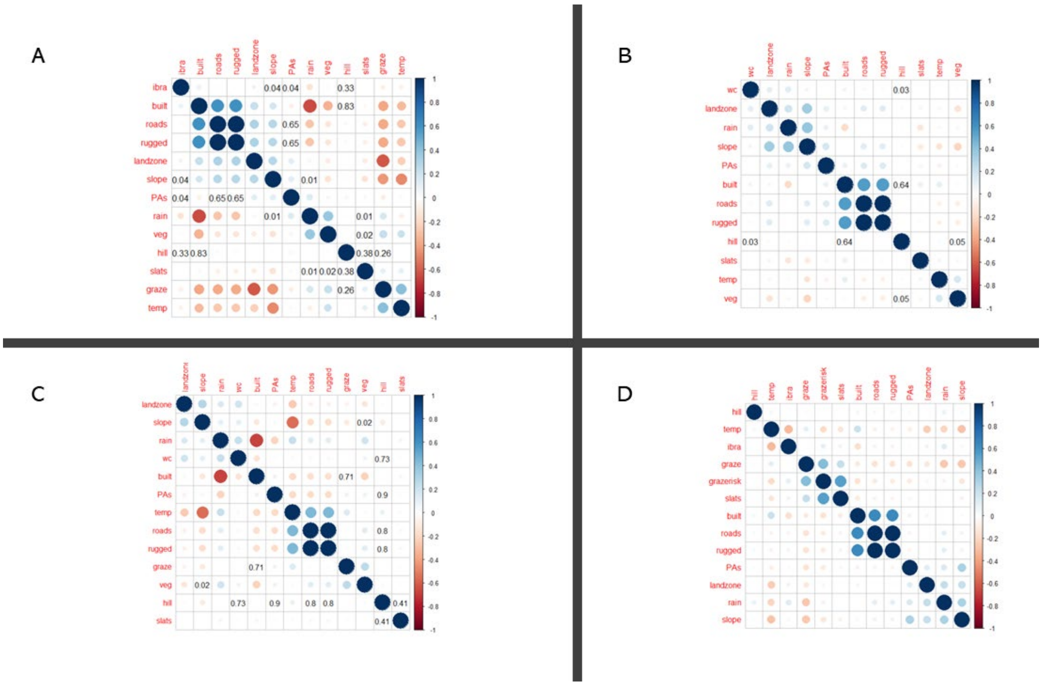


Figure A3-1: Correlation plot for co-variates in the Brigalow Belt (A), Cape York (B) Central Queensland Coast (C) and Desert Uplands (D). The colour of the text indicates the nature

of the correlation. Positive is shown in blue and negative correlation is shown in red. If the relationship is significant (p>0.01), then the value is displayed on the plot.

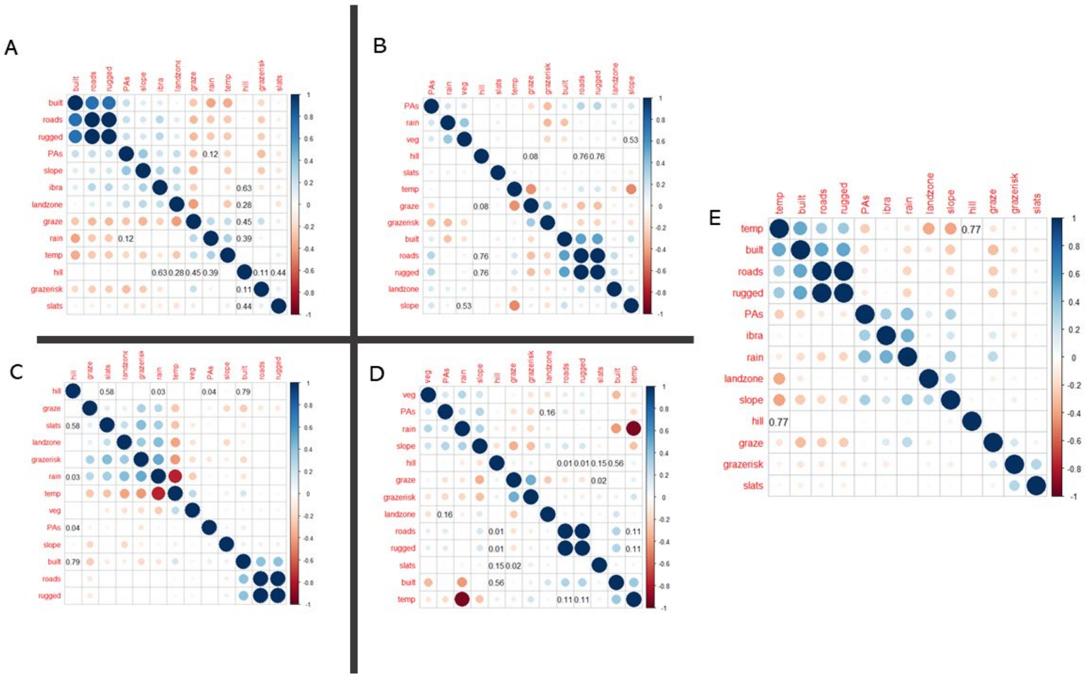


Figure A3-2: Correlation plot for co-variates in Einasleigh Uplands (A) and Mulga Lands (B), New England Tablelands (C) and Southeast Queensland (D) and Wet Tropics. The colour of the text indicates the nature of the correlation. Positive is shown in blue and negative correlation is shown in red. The value of a significant correlations (p>0.01) are shown on the plot.

A3.2 Sample sizes

TableA3-3 Sample sizes of the original data (total), after taking a 20% random sample, and after matching. The total matched area is the product of the number of pixels by 0.0625 or the area of one pixel in square kilometres.

	Total sample		*Random Sample*		*Matched sample*			*Matched Area (km²)*	
	Protected	Unprotected	Protected	Unprotected	Protected	Unprotected		Protected	Unprotected
Brigalow Belt	89,808	5,121,122	17,795	1,024,844	17,791	14,999	99.97	1,112	937.5
Cape York	190,750	1,440,788	38,230	288,078	38,230	24,600	100	2,389	1,537
Central Queensland Coast	8,337	190,358	1,673	38,066	1,673	1,358	100	104	84.89
Desert Uplands	23,829	946,519	4,855	189,215	4,729	3,197	94.40	291	209
Einasleigh Uplands	176,367	3,487,487	35,450	697,321	35,375	19,721	99.8	2,203	1,234
Mulga Lands	73,976	2,636,438	14,855	526,612	14,855	12,474	100	928	780
New England Tablelands	2,241	111,396	450	22,277	450	332	100	28	21
Southeast Queensland	96,590	794,024	19,445	158,678	19,444	12,704	99.9	1,215	794
Wet Tropics	118,296	149,762	23,690	30,047	23,663	9,568	99.9	1,479	598

Co-variate balance tables

Before matching, it is necessary to confirm non-random allocation of protected areas and thus the need for a statistical matching approach. We checked that protected and unprotected pixels were significantly different by comparing continuous co-variates between protected and unprotected pixels with absolute mean differences (**TableA3-4**) (Austin 2009b) in each bioregion. Absolute mean differences greater than 0.1 were considered significant (Austin 2011).

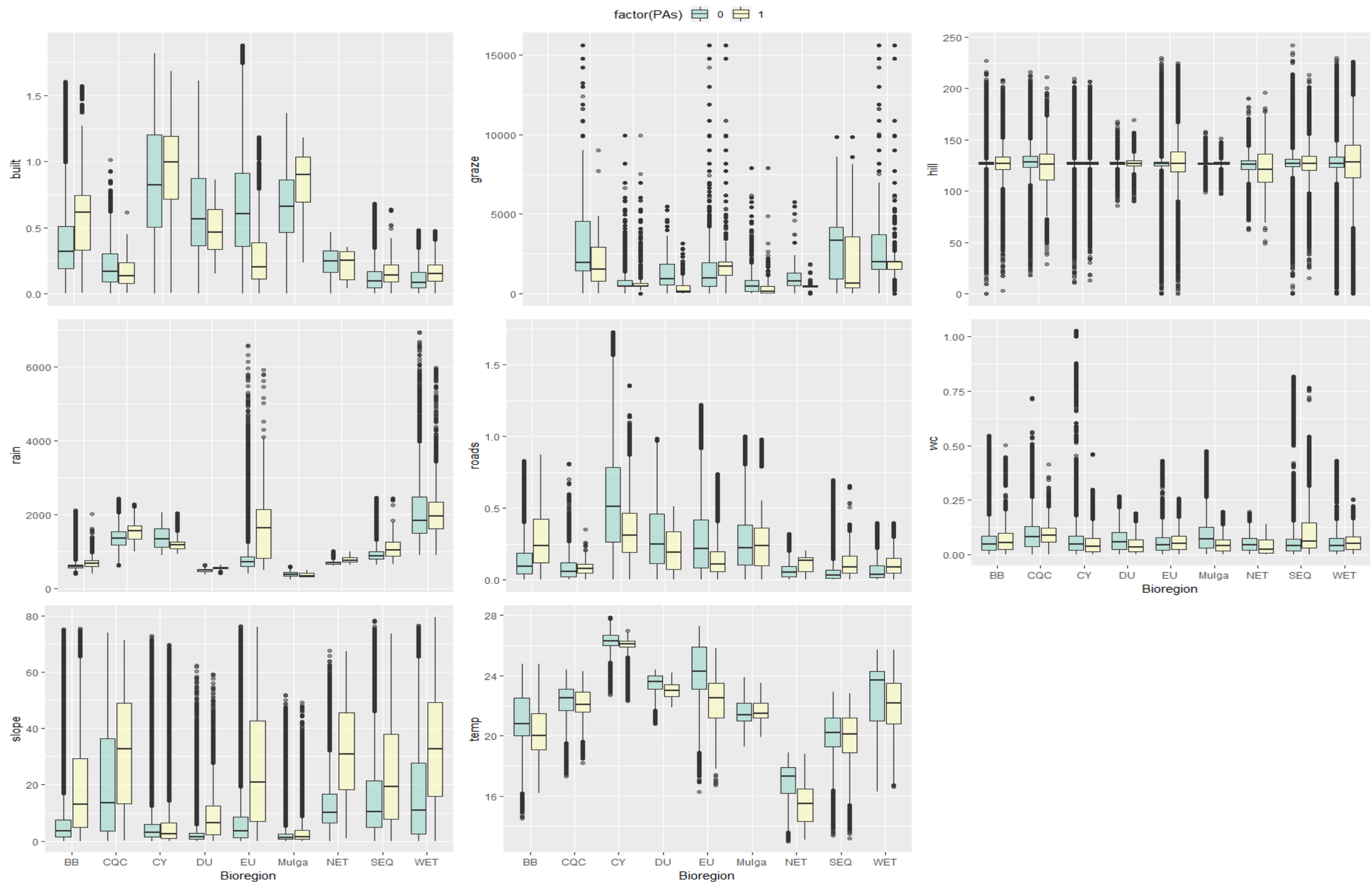


Figure A3-3 Boxplots showing the difference in co-variate values per bioregion. Built = distance to built up areas (decimal degrees), graze = grass biomass (kg/ha), hill = topographical shaded relief , rain = average annual rainfall (mm), roads = distance to State-controlled roads (decimal degrees) , wc = distance to major rivers (decimal degrees), slope = slope (per cent rise), temp = average annual temperature (OC).

In general, we found that protected pixels were located in areas with higher slopes and lower grass biomass than unprotected pixels. Protected pixels also tended to be further from urban centres in the Brigalow Belt and Cape York, but closer to urban centres than other bioregions. Protected area pixels also tended to be further from main roads than unprotected pixels, but were equally close to watercourses. Given that the characteristics of protected and unprotected pixels were dissimilar, I conclude that protected area placement was non-random across Queensland and a statistical matching approach was necessary for this context and some of these differences are further discussed in section "**Co-variate distributions**".

After matching, I evaluated this and a range of other test-statistics discussed in Section 2.2.4.1 of the main text. In Cape York, four of the seven co-variates were not balanced according to the Kolmogorov–Smirnov (KS) thresholds (<0.1): distance to built-up areas, average annual rainfall, distance to state-controlled roads, and average yearly temperature. These co-variates, however, were balanced for the other two test-statistics. We, therefore, considered that balance was sufficient in this bioregion. In the Central Queensland Coast, three co-variates (built-up areas, grass biomass and distance to roads) did not balance according to the KS threshold, and distance to roads did not balance according to the variance ratio (V) threshold (<2). All other co-variate were balanced in this bioregion, and all co-variates met, at a minimum, the absolute mean difference threshold (<0.25). We, therefore, concluded the matching algorithm produced reasonable balance.

In Cape York, four of the seven co-variates were not balanced according to the Kolmogorov–Smirnov (KS) thresholds (<0.1): distance to built-up areas, average annual rainfall, distance to state-controlled roads, and average yearly temperature. These co-variates, however, were balanced for the other two test-statistics. We, therefore, considered that balance was sufficient in this bioregion. In the Central Queensland Coast, three co-variates (built-up areas, grass biomass and distance to roads) did not balance according to the KS threshold, and distance to roads did not balance according to the variance ratio (V) threshold (<2). All other co-variate were balanced in this bioregion, and all co-variates met, at a minimum, the absolute mean difference threshold (<0.25) indicating a reasonable balance.

Table A3-4 Co-variate Balance tables for Cape York, Central Queensland Coast, Desert Uplands, Einasleigh Uplands, New England Tablelands, Mulga Lands, Southeast Queensland and the Wet Tropics. This table shows the co-variate name, type, mean average of the unprotected pixels from the random sample (M.Un.Ran), mean average of the protected pixels from the random sample (M.T.Ran) and their difference (Diff.Un). It then shows the mean average of the unprotected pixels after matching (M.Un.Mat), the mean average of the protected pixels after matching and their difference. The next columns assess how well the balance has performed against mean difference (M), variance ratios (V) and Kolmogorov–Smirnov (KS) thresholds. For each threshold, we provide a column which says "balanced" or "not-balanced" for each co-variate.

CAPE YORK

VARIABLE	M.Un.Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Mat	KS.Adj
PROPENSITY SCORE	0.10412	0.21537	0.93357	0.215059	0.215371	0.002612	1.016142	0.003636
BUILT-UP AREAS	0.85457	0.95715	0.31068	0.955427	0.957155	0.005234^	1.746837^	0.111509
GRASS BIOMASS	750.827	929.099	0.13934	1049.8	929.0992	-0.09434^	1.110445^	0.070442^
RAINFALL	1381.10	1202.11	-1.0651	1217.272	1202.119	-0.09018^	1.694063^	0.121397
DISTANCE TO ROADS	0.55281	0.35162	-0.9065	0.335026	0.351626	0.074797^	1.379577^	0.143264
SLOPE	5.55832	6.63065	0.10093	6.322172	6.630651	0.029036^	1.227147^	0.07345^
DISTANCE TO WATERCOURSE	0.06210	0.05524	-0.1266	0.059506	0.055241	-0.07874^	1.296074^	0.046534^
TEMPERATURE	26.2796	25.9475	-0.5903	25.96871	25.94755	-0.03761^	1.073728^	0.111248^

CENTRAL QUEENSLAND COAST

	M.Un.Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Mat	KS.Adj
PROPENSITY SCORE	0.03972	0.09623	0.92553	0.096107	0.096239	0.002154	1.001794	0.008368
BUILT-UP AREAS	0.21951	0.15126	-0.7458	0.173312	0.151262	-0.24095^	1.966466^	0.139868
GRASS BIOMASS	4170.77	1861.64	-2.0151	1839.079	1861.642	0.01969^	1.09788^	0.121937
RAINFALL	1361.53	1553.55	0.83436	1578.875	1553.556	-0.11001^	1.460217^	0.090257
DISTANCE TO ROADS	0.08163	0.08250	0.01968	0.093233	0.082508	-0.24254^	2.768563	0.163778

SLOPE	20.5858	31.8976	0.58251	33.8065	31.89766	-0.0983^	1.040778^	0.063359^
DISTANCE TO WATERCOURSE	0.09026	0.09794	0.13700	0.097153	0.09794	0.014035^	1.58678^	0.095039^
TEMPERATURE	22.2799	22.1047	-0.1500	21.87794	22.10478	0.194397^	1.306617^	0.095637^
DESERT UPLANDS								
	M.Un. Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
PROPENSITY SCORE	0.02005	0.21840	0.94351	0.218851	0.219256	0.001928	1.004296	0.005287
BUILT-UP AREAS	0.63758	0.47781	-0.8908	0.537771	0.479645	-0.32412	3.621503	0.175301
GRASS BIOMASS	126.987	127.410	0.06962	127.753	127.4426	-0.05108^	1.049735^	0.040178^
HILLSAHDE	1165.87	433.276	-1.1414	407.6995	440.1781	0.050606^	1.202334^	0.024318^
RAINFALL	504.919	550.775	0.86858	548.4578	550.0795	0.030718^	1.288339^	0.129837^
DISTANCE TO ROADS	0.30512	0.20554	-0.6965	0.252164	0.203913	-0.33754	1.310243^	0.120744
SLOPE	2.30741	9.07522	0.74398	10.94635	9.068705	-0.20641^	1.306278^	0.104673
DISTANCE TO WATERCOURSE	0.06997	0.04857	-0.4607	0.05052	0.048489	-0.04372^	1.141109^	0.074011^
TEMPERATURE	23.4522	23.1004	-0.5661	23.15067	23.10588	-0.07207^	1.000376^	0.124551
EINASLEIGH UPLANDS								
	M.Un.Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
PROPENSITY SCORE	0.03351	0.34076	1.06221	0.340674	0.341396	0.002498	1.005968	0.005512
BUILT-UP AREAS	0.66244	0.28628	-1.5420	0.262235	0.286038	0.097578^	1.229809^	0.165965
GRASS BIOMASS	1447.22	1625.16	0.18465	1721.507	1628.129	-0.0969^	1.667059^	0.062869^
RAINFALL	791.942	1630.49	1.06713	1672.702	1632.692	-0.05092^	1.235506^	0.056254^
DISTANCE TO ROADS	0.28628	0.15625	-0.9030	0.147405	0.156057	0.060094^	1.280923^	0.152565
SLOPE	7.58206	25.5322	0.89047	24.71482	25.56332	0.042093^	1.060055^	0.027901^
DISTANCE TO WATERCOURSE	0.05487	0.06170	0.14254	0.061823	0.061733	-0.0019^	1.106627^	0.021823^
TEMPERATURE	24.3948	22.3786	-1.3151	22.4715	22.37736	-0.06141^	1.294924^	0.097046^
MULGA LANDS								
	M.Un. Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
PROPENSITY SCORE	0.02625	0.06924	0.72135	0.069183	0.069247	0.001085	1.003327	0.005318
BUILT-UP AREAS	0.65915	0.82099	0.61903	0.830651	0.820997	-0.03693^	1.185971^	0.174285
GRASS BIOMASS	759.879	365.628	-0.7146	366.6417	365.6283	-0.00184^	1.541208^	0.191181
RAINFALL	391.238	374.062	-0.3063	370.2409	374.0629	0.068172^	1.23725^	0.153753

Distance to roads	0.25658	0.26219	0.02729	0.241586	0.262194	0.100322^	1.213252^	0.081252^
Slope	2.10774	3.31311	0.24984	2.744923	3.313118	0.117771^	1.478992^	0.067385^
Distance to watercourse	0.09159	0.0486	-1.1737	0.051264	0.0486	-0.07273^	1.508507^	0.035544^
Temperature	21.5686	21.8059	0.30971	21.7872	21.80599	0.024522^	1.175975^	0.106631

New England tablelands

	M.Un. Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
Propensity score	0.01497	0.25888	1.06771	0.247925	0.258884	0.047972	1.079363	0.033333
Built-up areas	0.24174	0.21854	-0.2233	0.223571	0.218545	-0.0484^	1.326236^	0.140000
Grass biomass	955.914	381.595	-1.9227	371.9733	381.5956	0.03221^	1.160334^	0.044444^
Rainfall	706.914	792.384	1.22797	781.7622	792.3844	0.152613^	1.256897^	0.124444
Distance to roads	0.06693	0.11631	0.85339	0.121188	0.116319	-0.08414^	1.25335^	0.113333
Slope	12.9876	34.5093	1.33022	35.50786	34.50934	-0.06172^	1.040359^	0.084444^
Distance to watercourse	0.05202	0.04374	-0.2005	0.040889	0.04374	0.069077^	1.612889^	0.164444

Southeast Queensland

	M.Un. Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
Propensity score	0.09052	0.26125	0.87662	0.258366	0.26126	0.01486	1.069327	0.018618
Built-up areas	0.11612	0.15795	0.43913	0.135678	0.157952	0.233878^	1.402132^	0.177844
Grass biomass	3127.03	1853.41	-0.5834	1763.492	1853.307	0.041143^	1.080654^	0.041144^
Rainfall	945.415	1076.11	0.58191	1128.986	1076.115	-0.23539^	1.525515^	0.13958
Distance to roads	0.05009	0.11245	0.75047	0.092455	0.112456	0.240739^	1.550744^	0.165347
Slope	15.4705	23.9017	0.46002	24.0808	23.8997	-0.00988^	1.002335^	0.017435^
Dist to watercourse	0.05669	0.11316	0.46747	0.100169	0.113164	0.107582^	1.399112^	0.088099^
Temperature	20.1371	19.9334	-0.1267	20.00483	19.93355	-0.04436^	1.266669^	0.08239^

Wet tropics

	M.Un. Ran	M.T.Ran	Diff.Ran	M.Un.Mat	M.T.Mat	Diff.Adj	V.Ratio.Adj	KS.Adj
Propensity score	0.34426	0.55974	1.22258	0.559791	0.559656	-0.00077	1.001027	0.002893
Built-up areas	0.11756	0.16319	0.49188	0.136269	0.163216	0.290445	1.178195^	0.185349
Grass biomass	3955.37	1968.93	-2.3266	1928.898	1969.449	0.047496^	1.421905^	0.074531^
Rainfall	2042.33	2051.57	0.01541	2195.842	2051.193	-0.24134^	1.586726^	0.126133

DISTANCE TO ROADS	0.07044	0.10558	0.48968	0.091865	0.10559	0.191298^	1.156129^	0.154635
SLOPE	17.5062	32.7508	0.78678	34.27019	32.744	-0.07877^	1.001409^	0.044923^
DISTANCE TO WATERCOURSE	0.05141	0.05931	0.18493	0.057833	0.059315	0.034698^	1.005235^	0.040328^

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A3.3 Propensity score distributions

The goal of matching is to successfully identify untreated pixels which are statistically similar to treated pixels. The success of a matching algorithm can be scrutinised with an evaluation of the propensity score. The propensity score is the probability of treatment given a set of co-variates. I graphed the distribution of propensity score values for both protected and unprotected pixels before (unadjusted) and after (adjusted) matching for each of the nine bioregions using the Cobalt (Greifer 2018) package. In these figures, the proportion of pixels on the y-axis and the propensity score on the x-axis. Protected pixels are shown in blue (Treat, 1) and unprotected pixels are shown in red (Treat, 0). In general, the propensity score distributions for protected and unprotected pixels were similar after matching, discussed for each bioregion below.

In general, I found that the propensity score distributions were near-identical between protected and unprotected pixels after matching for all bioregions. That is, the pixels included in the matched data set had an equal distribution of the probability of receiving protection irrespective of whether or not they were, in fact, protected. For example, before matching, a large number of unprotected pixels across bioregions had a low slope creating a peak at low slopes in the distribution of unprotected pixels. After matching, the number of unprotected pixels with a low slope was reduced, and the distribution of slope values in unprotected pixels resembled that of protected pixels. This first diagnostic suggested the successful isolation of counterfactual pixels, so we continued evaluating the match quality with numerical diagnostics.

Brigalow Belt:

Overall, the differences in the distribution of propensity scores values in the matched (adjusted) samples for protected and unprotected pixels were reduced with matching. Before matching, approximately 90% of all unprotected pixels had between 0-0.5% probability of protection and less than 0.5% of unprotected pixels had a propensity score higher than 0.15%. Before matching, the propensity score for the protected pixels ranged from 0.00-0.75. The majority (50%) of protected pixels had a propensity score of 0.00. Approximately 1.5% of protected pixels had a propensity score higher than 0.50. After matching, the proportion of unprotected pixels with a propensity score around 0.00 was nearly halved and was equal to the proportion of protected pixels with a similar propensity score. The unprotected pixels propensity score range included a higher proportion of pixels with a propensity score greater than 0.25.

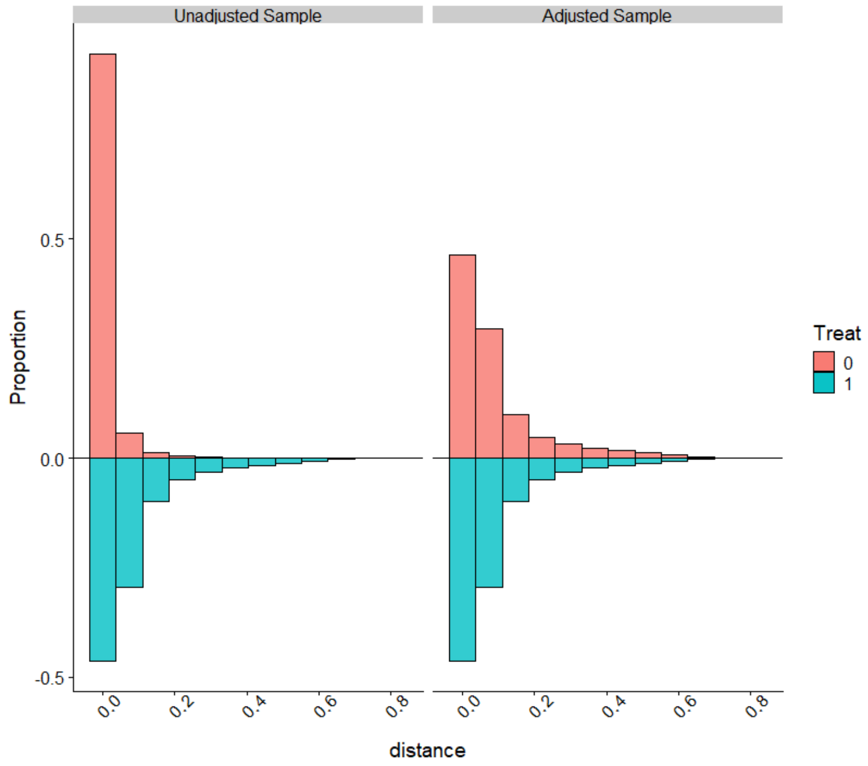


Figure A3-4: Propensity score distribution for the Brigalow Belt.

Cape York

Before matching (unadjusted), over 70% of unprotected pixels had a probability of being protected less than 0.25, and the propensity score for the protected pixels ranged from 0.00-0.50 with approximately 40% having a propensity score equal to or greater than 0.25. After matching, the distribution of propensity score values between protected and unprotected pixels was near identical. I can reasonably infer that matching had successfully improved the similarity between protected and unprotected pixels.

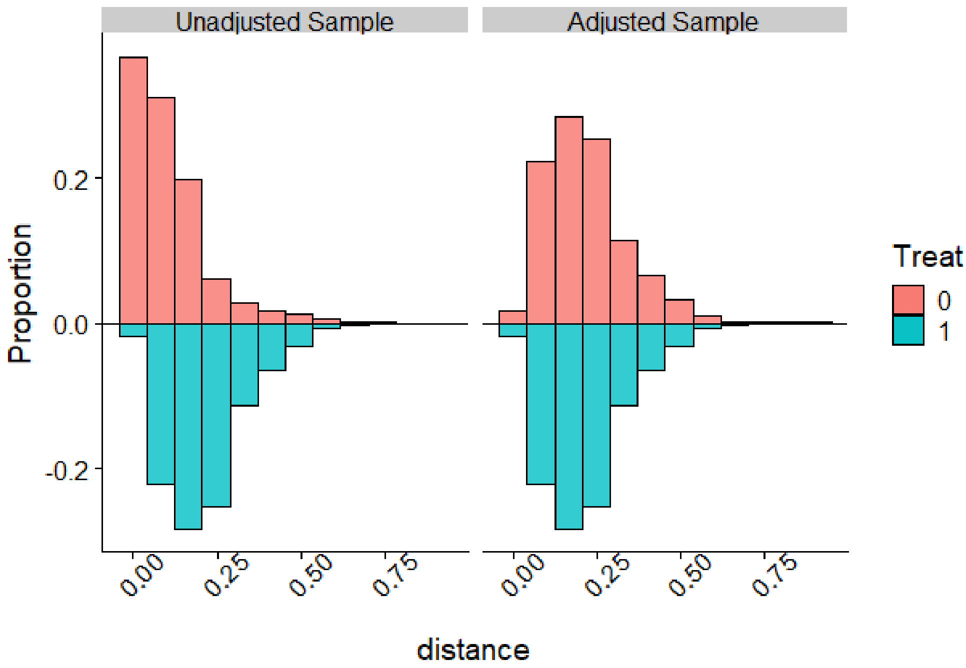


Figure A3-5: Propensity score distribution for Cape York.

Central Queensland Coast

Before matching, 85% of unprotected pixels had a propensity score less than 0.25, and the propensity score for the protected pixels ranged from 0.00-0.55 where and 75% of protected pixels had a propensity score <0.30). After matching, the proportion of unprotected pixels with a propensity score around 0.00 was reduced by nearly 90% and was equal to the proportion of protected pixels with the same propensity score. I concluded, therefore, that matching had successfully improved the similarity between protected and unprotected pixels.

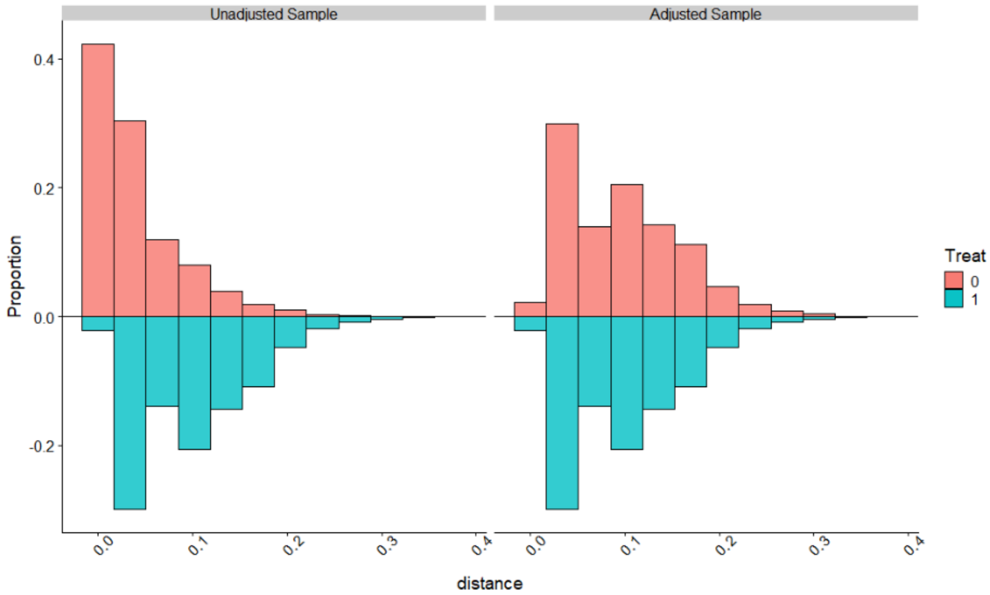


Figure A3-6: Propensity score distribution for the Central Queensland Coast.

Desert Uplands

Before matching, 90% of unprotected pixels had a propensity score less than 0.15, and the propensity score for the protected pixels ranged from 0.00-0.60 where 60% of protected pixels had a propensity score <0.25. After matching, the proportion of unprotected pixels with a propensity score of around 0.00 was reduced by nearly 40%. I concluded, therefore, that matching had successfully improved the similarity between protected and unprotected pixels.

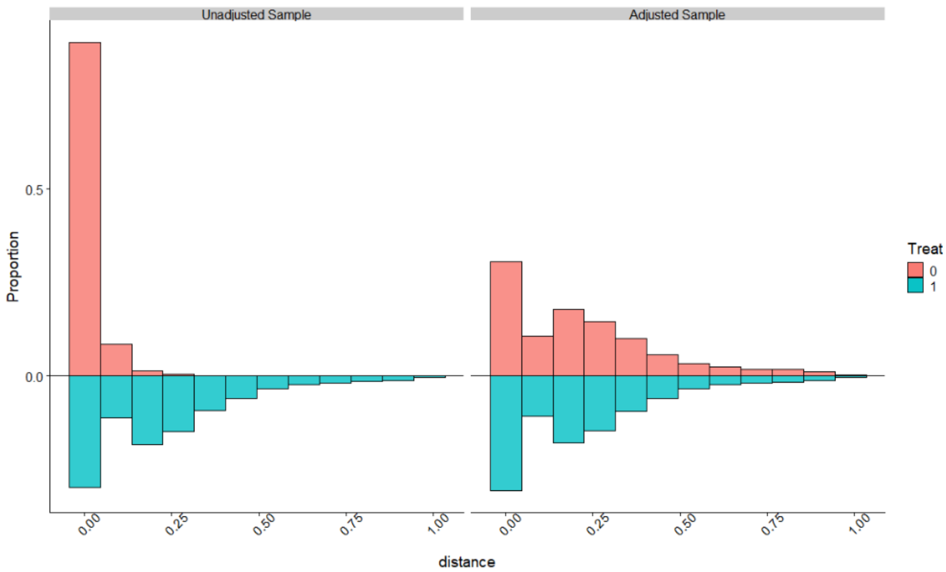


Figure A3-7: Propensity score distribution for the Desert Uplands.

Einasleigh Uplands

Before matching, approximately 88% of unprotected pixels had a propensity score of less than 0.1, and the propensity score for the protected pixels ranged from 0.00-0.80 with an even distribution throughout. After matching, the proportion of unprotected pixels with a propensity score of around 0.00 was reduced by nearly 60%. I concluded, therefore, that matching had successfully improved the similarity between protected and unprotected pixels.

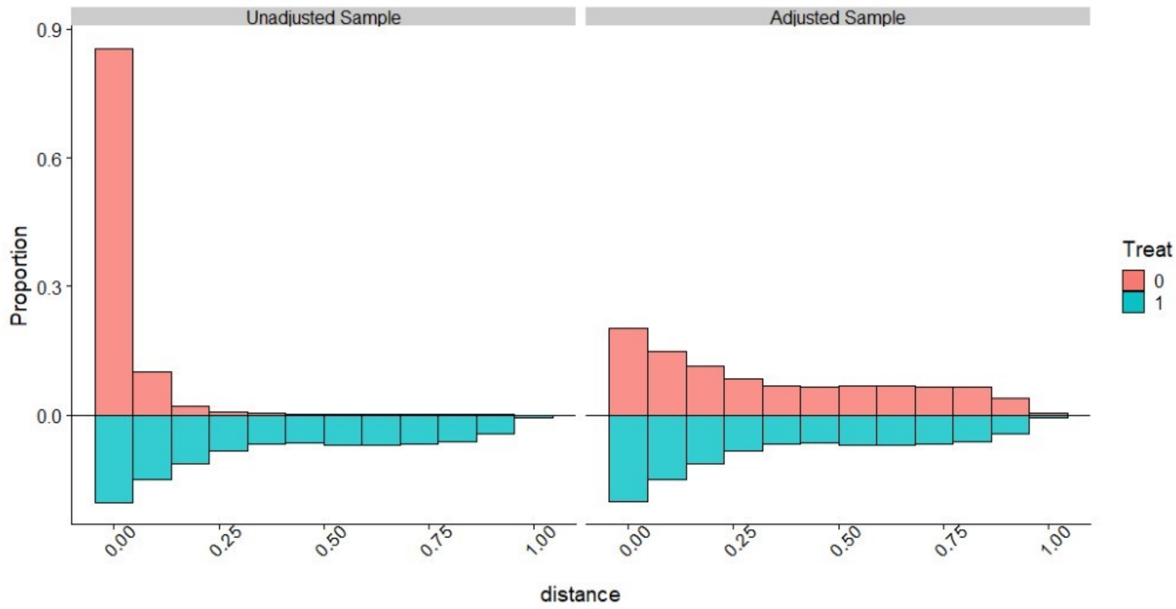


Figure A3-8: Propensity score distribution for the Einasleigh Uplands.

Mulga Lands

Before matching, 90% of unprotected pixels had a propensity score of less than 0.1, and the propensity score for the protected pixels ranged from 0.00-0.25. Approximately 50% of protected pixels had a propensity score of 0.1. After matching, the proportion of unprotected pixels with a propensity score of around 0.00 was reduced by nearly 50%. I concluded, therefore, that matching had successfully improved the similarity between protected and unprotected pixels.

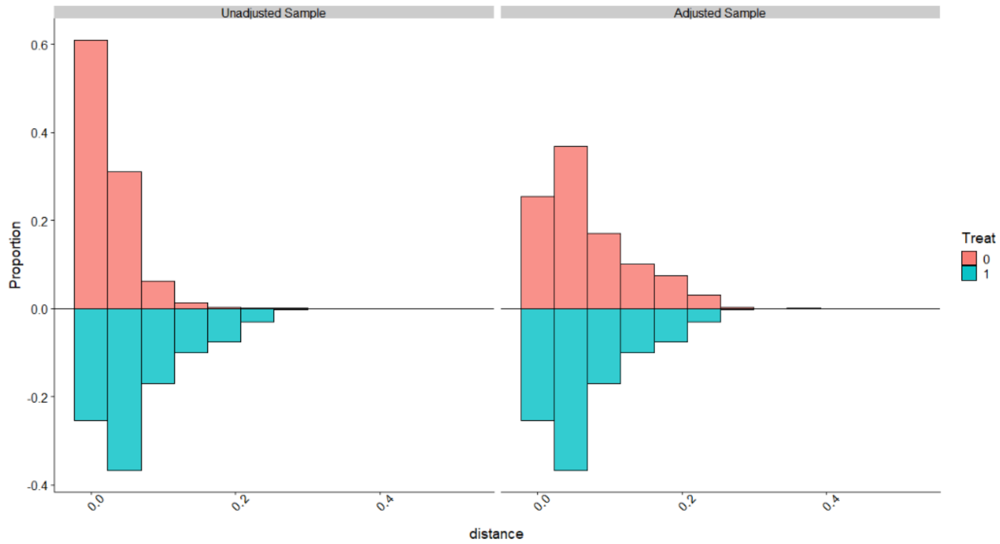


Figure A3-9: Propensity score distribution for the Mulga Lands.

New England Tablelands

Before matching, 91% of unprotected pixels had a propensity score of less than 0.1, and the propensity score for the protected pixels ranged from 0.00-0.75. Approximately 60% of protected pixels had a propensity score of less than 0.15. After matching, the proportion of unprotected pixels with a propensity score of around 0.00 was reduced by nearly 60%. I concluded, therefore, that matching had successfully improved the similarity between protected and unprotected pixels.

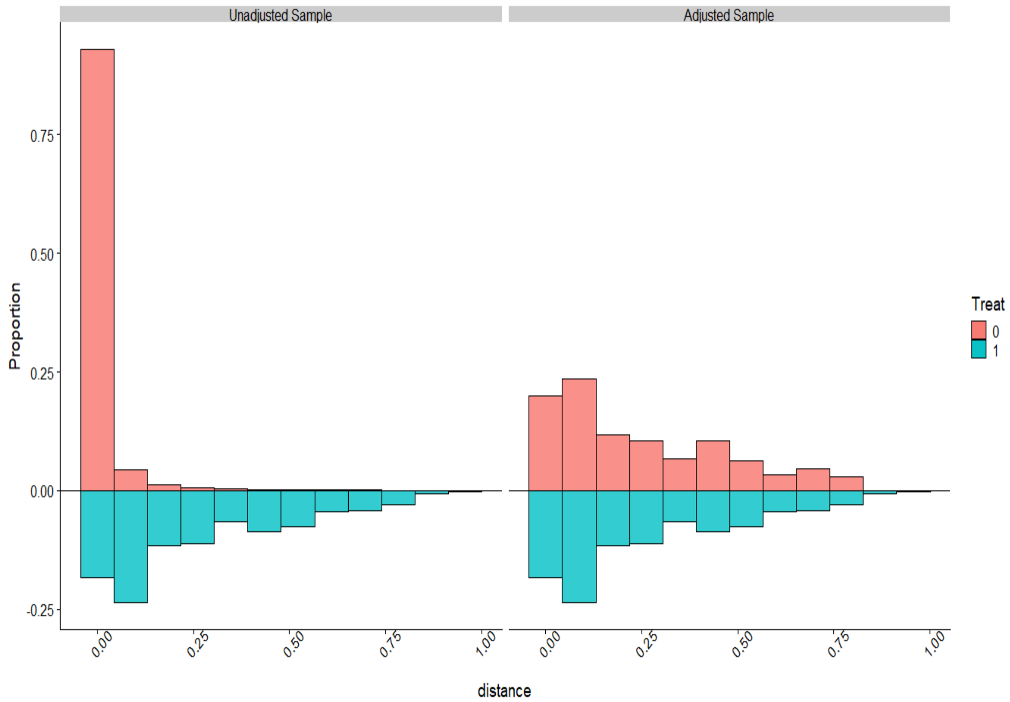


Figure A3-10: Propensity score distributions for the New England Tablelands.

Southeast Queensland

Before matching, 80% of unprotected pixels had a propensity score around 0.00, and the propensity score for the protected pixels ranged from 0.00-0.75. Approximately 50% of protected pixels had a propensity score of 0.15. After matching, the proportion of unprotected pixels with a propensity score of around 0.00 was reduced by nearly 80%. Overall, the propensity scores in the adjusted samples between the protected and unprotected pixels were near-identical after matching.

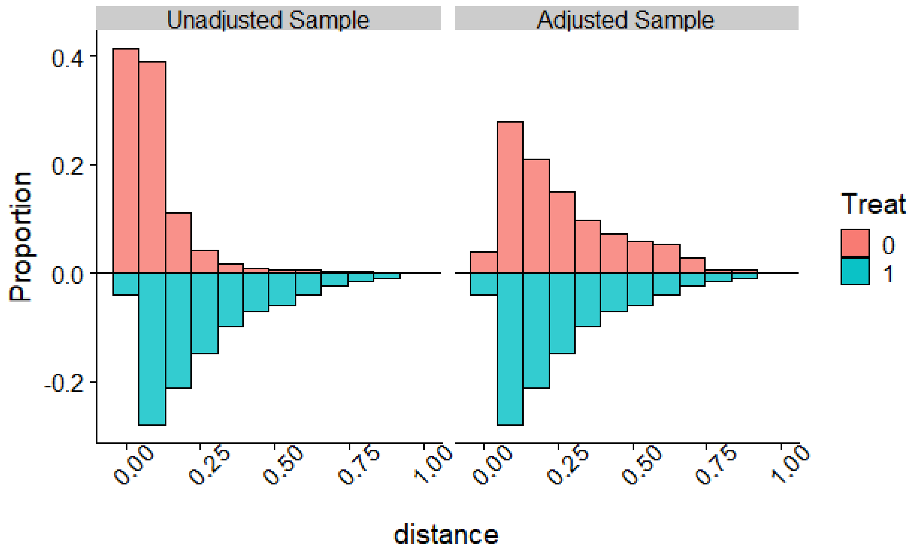


Figure A3-11: Propensity score distribution for Southeast Queensland.

Wet Tropics

Before matching, 80% of unprotected pixels had a propensity score around 0.00, and the propensity score for the protected pixels ranged from 0.00-0.75. Approximately 50% of protected pixels had a propensity score of 0.15. After matching, the proportion of unprotected pixels with propensity scores near 0.00 were reduced by nearly 80%. I concluded, therefore, that matching improved the similarity between protected and unprotected pixels.

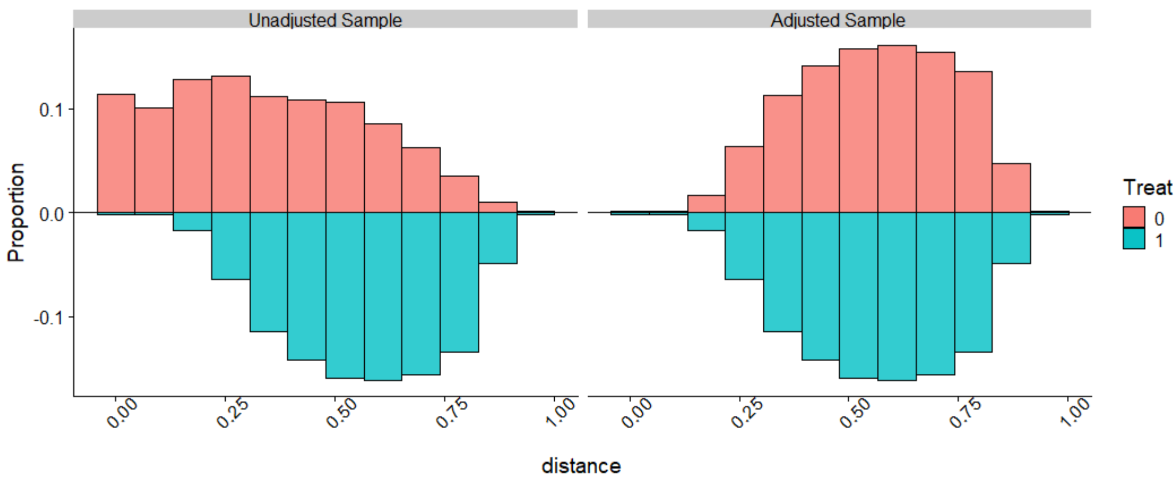


Figure A3-12: Propensity score distribution for Wet Tropics.

A3.4 Co-variate distributions

This analysis compares the range of values for each co-variate for protected and unprotected pixels and looks for overlap in these distributions after matching. This visual diagnostic is critical to ensuring that the matching analysis has appropriately captured the ranges of values associated with each co-variate and eliminated untreated pixels with significantly different values. I produced co-variate distribution graphs in Cobalt (Greifer 2018) for each bioregion and co-variates included in the analysis.

Brigalow Belt

The unmatched (unadjusted) co-variate distribution is different in the protected and unprotected groups for all co-variates in the Brigalow Belt (Figure 12). For example, protected cells had an average distance to built-up areas (a) of 0.75, whereas unprotected cells tended to be around 0.25. On average, unprotected pixels are closer to built-up areas than protected pixels before matching. After matching, the unprotected cells are further from built-up areas. Similarly, for rainfall (mm) before matching, many of the unprotected pixels have rainfall around 500m. After matching, more cells with lower rainfall are removed, rendering the distributions more similar. Unprotected cells tended to be closer to State-controlled roads, many of which had a peak of 0.01. That peak was removed after matching. Likewise, unprotected cells also tended to have lower slopes (between 5-40%). After matching, the distribution of slopes between protected and unprotected pixels were closely matched.

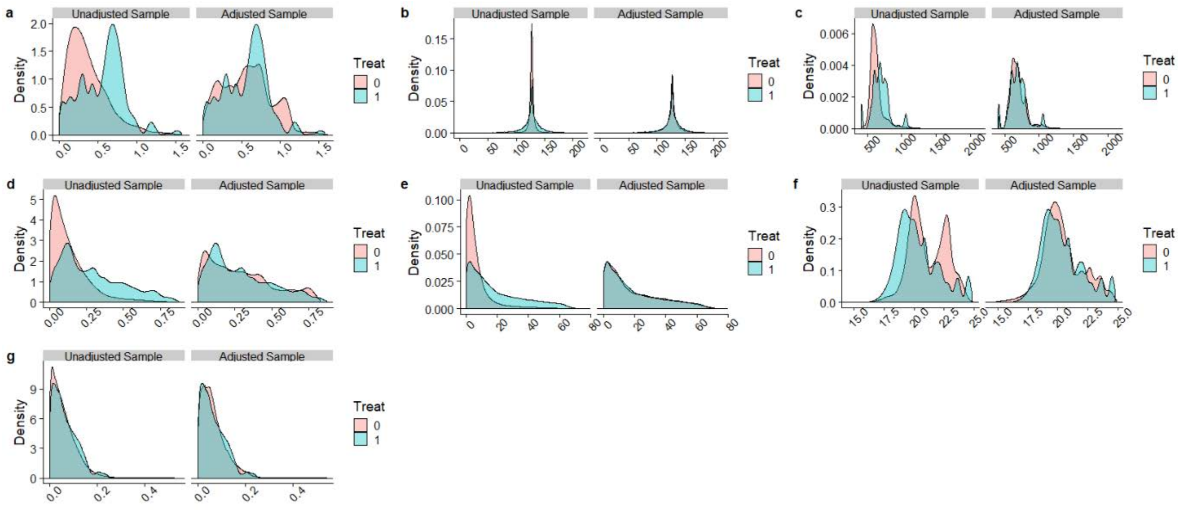


Figure A3-13: Distribution of co-variates before and after treatment for the Brigalow Belt. The distribution in red shows the unprotected pixels. The distributions in blue show the protected pixels. Balance plots graph the co-variate ranges for protected and unprotected pixels in the adjusted and adjusted sample and are used to assess how well the distributions between protected and unprotected pixels overlap after matching. A = Distance to Built-up areas, B= Hillshade, C = Rainfall D = Distance to major roads, E = Slope, F = Temperature, and G = Distance to major watercourses.

Cape York

The unmatched (unadjusted) co-variate distribution are quite different in the protected and unprotected groups for built-up areas, rainfall and distance to roads. For grazing capacity, slope and distance to watercourses, the distributions are quite similar. Protected pixels have a peak distance to built-up areas of 1.0, whereas unprotected pixels had a near-normal distribution between 0.0 and 1.5. That means that the largest proportion of protected pixels were further to built-up areas than unprotected pixels in the unmatched sample. After matching, the distributions have more overlap. Before matching, protected pixels have two peaks at 900mm and 1200mm where unprotected pixels have peaks at 1000mm and 1600mm. After matching, the unprotected peak at 1600mm is removed, and the distributions are more similar. Unprotected pixels tended to have a higher grazing capacity than protected pixels before matching. There is one state-controlled road in Cape York, and protected pixels tended to be closer to the roads before matching. After matching, more unprotected pixels were included, which were closer to the state road. The slope was similar before and after matching with both protected and unprotected pixels having a peak 0-5% rise. This suggests that there is not a lot of topographical variation in the Cape York bioregion. Similarly, most pixels (protected and unprotected) were close to watercourses. Neither treatment groups had many pixels which exceeded 0.25 degrees.

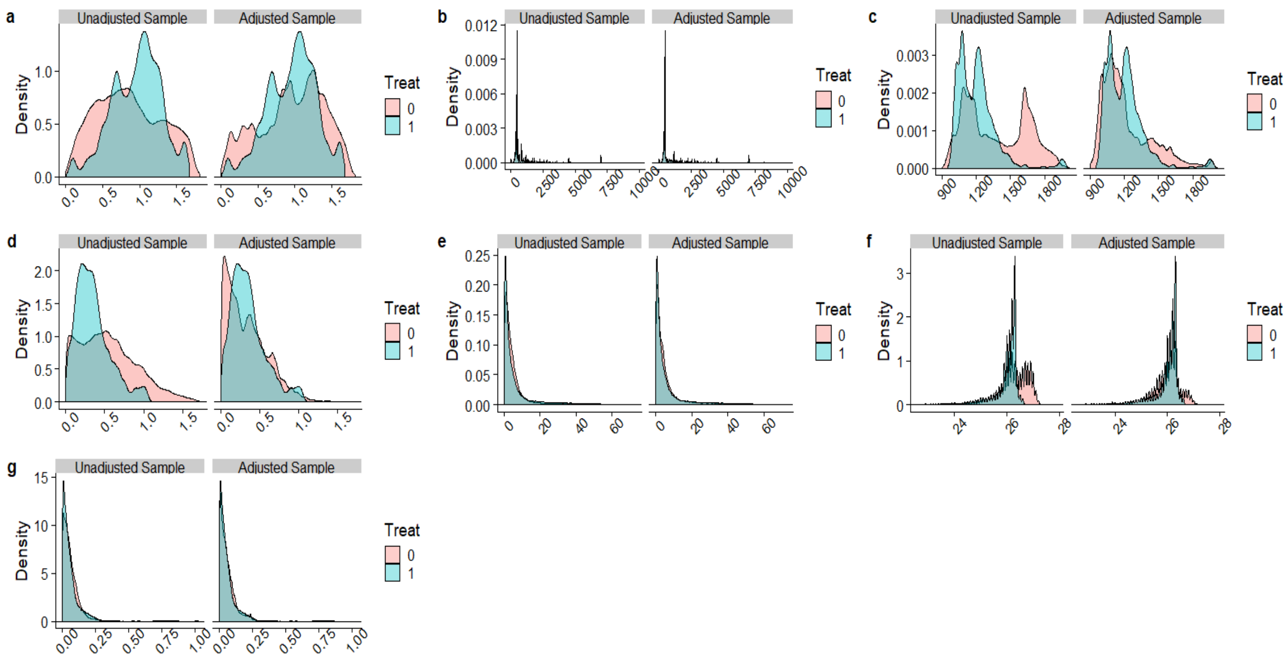


Figure A3-14: Co-variate distribution by treatment category for Cape York. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Rainfall D = Distance to major roads, E = Slope, F = Temperature, and G = Distance to major watercourses.

Central Queensland Coast

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected groups for built, graze, rain and slope. For example, protected pixels have a peak distance to built-up areas of between 0.1-0.2, whereas unprotected pixels had left-skewed near-normal distribution between 0.0 and 0.8. That means that the largest proportion of protected pixel was closer to built-up areas than unprotected pixels in the unmatched sample. After matching, the distributions have more overlap. Before matching, protected pixels have two peaks at 1200mm and 1600mm where unprotected pixels have a greater distributional range and smaller peaks. After matching, the unprotected peak pixels have the highest proportion between 1200 and 1700mm; however, there are a proportion of pixels with peaks at 1200 and 1600 - double the highest peak for unprotected pixels. More than double the number of unprotected pixels had a slope around 0.0 before matching. This peak was substantially reduced after matching. Unprotected and protected pixels had a similar distribution in the values for grazing capacity except. One major difference, however, was a peak for unprotected pixels at 15,000kg/ha. In contrast, very few protected pixels had a grazing capacity greater than 5,000. Matching excluded unprotected pixels with a high grazing capacity. The largest proportion of unprotected pixels which are close to roads (0.0) is nearly 3x greater than protected pixels in the unmatched sample. This peak is removed, and the distributions are more similar after matching; however, this co-variate was still unbalanced (See above co-variate balance tables). Similarly, most pixels (protected and unprotected) were close to watercourses. Neither treatment groups had many pixels which exceeded 0.4 degrees.

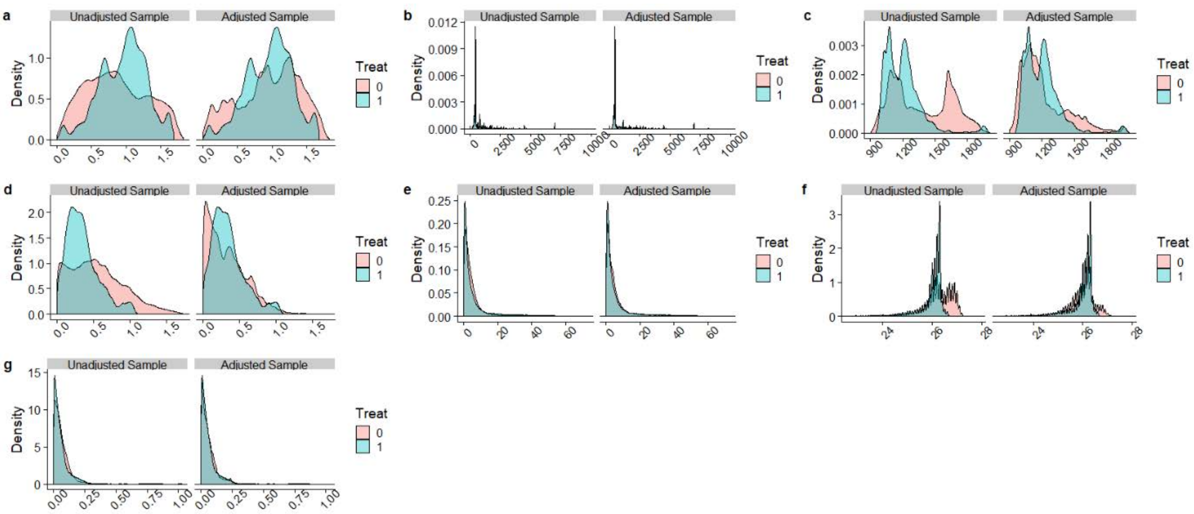


Figure A3-15: Co-variate distribution by treatment category for Central Queensland Coast. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Rainfall D = Distance to major roads, E = Slope, F = Temperature, and G = Distance to major watercourses.

Desert Uplands

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected groups for built, rain, roads, wc and slope. For example, unprotected pixels have a peak distance to built-up areas of between 0.0-1.5 whereas protected pixels had three peaks at 0.1, 0.25 and 0.7 and few were further than 0.7. That means that the largest proportion of protected pixel was closer to built-up areas than unprotected pixels in the unmatched sample. This co-variate was poorly balanced (See co-variate balance table above). Before matching, protected pixels have two peaks at 450mm and 550mm where unprotected pixels have a greater distributional range between 350 and 600. After matching, the unprotected peak pixels have the highest proportion between 500 and 600mm. More than 2x the number of unprotected pixels had a slope around 0.0 before matching. Matching produced a near-identical distributional range for protected and unprotected pixels. More unprotected pixels had a higher grazing capacity (<1000kgha). Matching reduced the proportion of unprotected pixels with a high grazing capacity resulting in a near-identical distributional overlap. Before matching, unprotected pixels were mostly close to roads (0.00-0.25) however, the proportion tapered towards 0.99. Protected pixels, however, were all between 0.00 and 0.50. Most pixels in the Desert Uplands were close to watercourses - neither treatment groups had many pixels which exceeded 0.3 degrees.

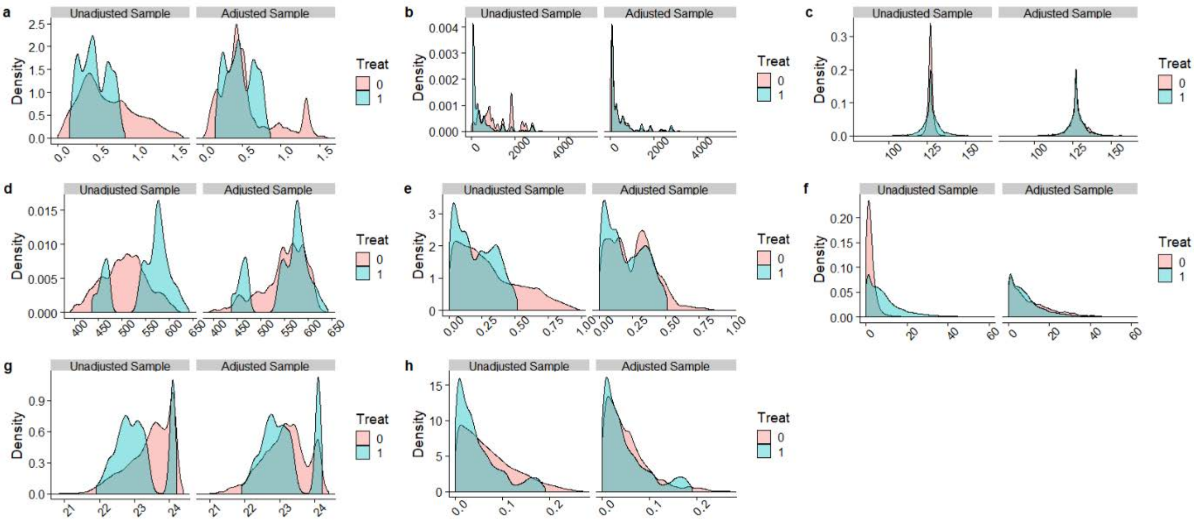


Figure A3-16: Co-variate distribution by treatment category for Desert Uplands. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Hillshade D = Rainfall , E = Distance to major roads, F = Slope, G = Temperature, and H = Distance to major watercourses.

Einasleigh Uplands

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected pixels for built, rain, roads and slope. For example, protected pixels have a peak distance to built-up areas of between 0.0-.25, whereas unprotected pixels evenly range between 0.0 and 2.0. That means that the largest proportion of protected pixel was closer to built-up areas than unprotected pixels in the unmatched sample. Before matching, protected pixels have two peaks at 500mm and 2000mm where unprotected are almost all less than 1000mm. Matching produced a near-identical overlap. Nearly three times the number of unprotected pixels had a slope around 0.0 before matching. Matching produced near-identical distributions protected and unprotected pixels by having an almost even distributional range between 0-70%. In this bioregion, grazing capacity was similar between treatment groups before matching where most pixels had a grazing capacity less than 5000kg/ha. Matching produced near-identical distributional overlap between protected and unprotected pixels. Before matching, protected pixels were mostly close to roads (0.00-0.25) with another small peak at 0.5 whereas unprotected pixels had a left-skewed distribution which ranged from 0.0-1.25. After matching, all pixels which were further than 0.60 were removed, producing a better overlap. Similarly, most pixels (protected and unprotected) were close to watercourses. Neither treatment groups had many pixels which exceeded 0.25 degrees.

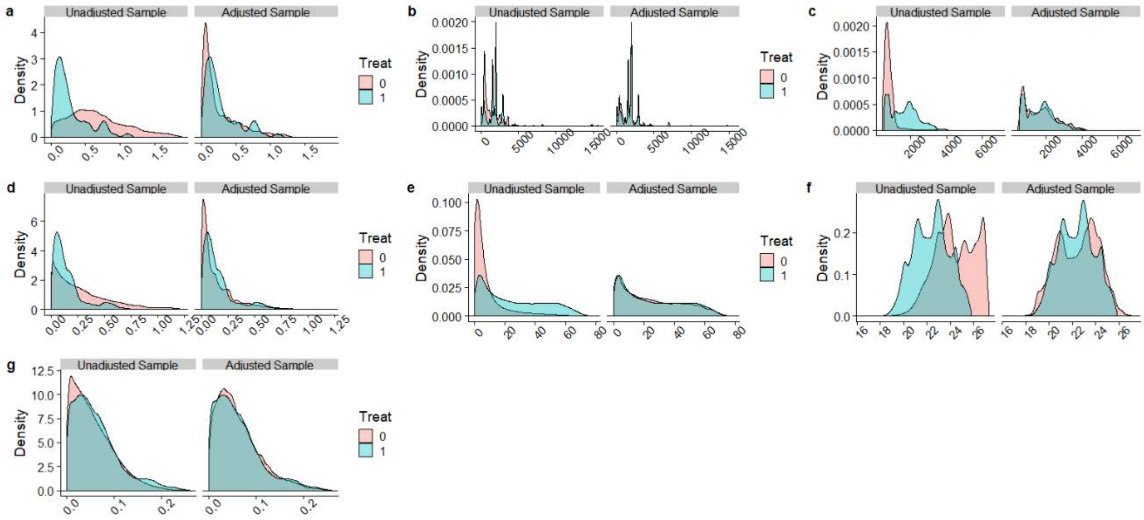


Figure A3-17: Co-variate distribution by treatment category for Einasleigh Uplands. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Rainfall, D = Distance to major roads, E = Slope, F = Temperature, and G = Distance to major watercourses.

Mulga Lands

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected pixels for built, rain, and slope. For example, protected pixels have two peaks for distance to built-up areas of (one at 0.25 and another at 0.75 to 1.0). Unprotected pixels, however, ranged evenly between 0.0 and 1.25. That means that most protected pixels were closer to built-up areas than unprotected pixels in the unmatched sample. Before matching, protected pixels have three peaks at 320, 400 and 450mm whereas unprotected are evenly spread between 250 and 600mm. After matching, most unprotected pixels had an average annual rainfall of 300mm and 400mm. Slope distribution was near identical before matching. Most pixels (protected and unprotected) were close to watercourses, however more protected pixels were closer, and unprotected pixels ranged to 0.4 degrees. After matching, no unprotected pixels exceeded 0.2, and almost all were between 0.00 and 0.1. Grazing capacity was similar in the bioregion; however, a small peak of unprotected pixels had a grazing capacity at 6,000. This peak was removed after matching. Before matching, distance to roads for unprotected pixels had the highest proportion at 0.00 and then evenly declined to 0.75. There were no protected pixels with a distance to roads between 0.5 and 0.75. Matching produced a sample in which most unprotected pixels were between 0.00 and 0.5.

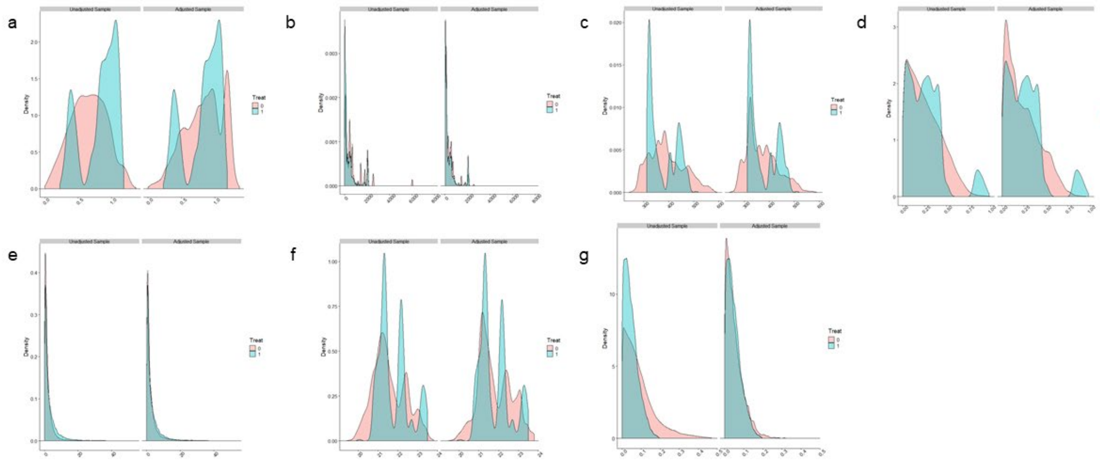


Figure A3-18: Co-variate distribution by treatment category for Mulga Lands. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= Grass biomass, C = Rainfall, D = Distance to major roads, E = Slope, F = Temperature, and G= Distance to major watercourses.

New England Tablelands

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected pixels for built, rain, roads and slope. For example, protected pixels have two peaks for distance to built-up areas of between at 0.01 between 0.2-0.3. In contrast, unprotected pixels evenly range between 0.0 and 0.4. Matching produced a higher number of unprotected pixels with the peaks observed in protected pixels. Before matching, there were no protected pixels with rainfall less than 650mm whereas almost all unprotected pixels were less than 800mm. Matching selected unprotected pixels with a rainfall range between 650 and 1000mm producing a range that overlapped with protected pixels. Before matching, there were triple the number of unprotected pixels with a slope that ranged from 0 to10%, and very few pixels had a slope higher than 20%. Protected pixels had a slope that ranged between 0 and 60%. Matching removed nearly all the low slope unprotected pixels to produce a similar distribution. Before matching, most of the unprotected pixels had a grazing capacity at 1000 and 2000, and there were almost no protected pixels with a grazing capacity greater than 700. These unprotected peaks were removed after matching. Before matching, distance to roads for unprotected pixels had the highest proportion at 0.00 and evenly declined to 0.3. Matching produced a sample in which most unprotected pixels were around 0.1, or the average of the protected peaks. The distribution for watercourses was similar before matching except that more protected pixels were between 0.0 and 0.2. After matching, more unprotected pixels were closer to watercourses.

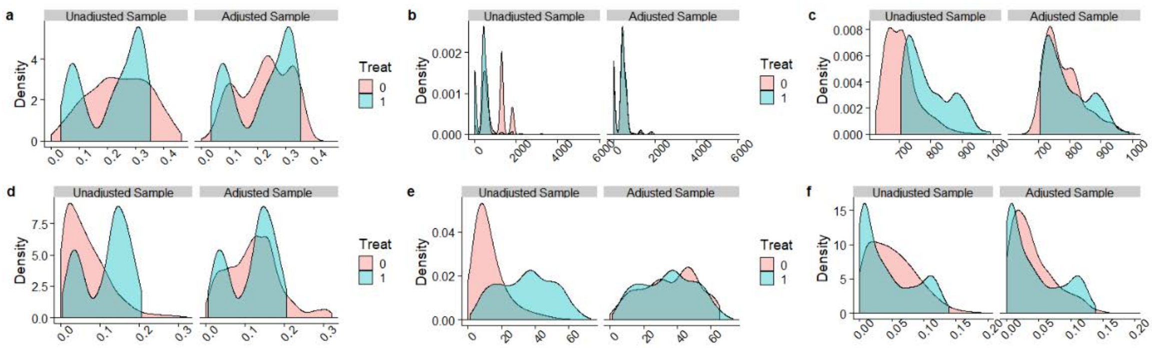


Figure A3-19: Co-variate distribution by treatment category for New England Tablelands. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Rainfall, D = Distance to major roads, E = Slope, and F= Distance to major watercourses.

Southeast Queensland

The unmatched (unadjusted) co-variate distributions are quite different in the protected and unprotected pixels for graze, rain, roads and slope. Most protected pixels were 0.1 dd to built-up areas and between 0.2 and 0.4; however, most unprotected pixels are less than 0.1. Before matching, there were more unprotected pixels with a high grazing capacity (>2500kg/ha), and there were almost a few protected pixels with a grazing capacity greater than 5000kg/ha. High grazing capacity unprotected pixels were removed after matching to produce near-identical distributions. Before matching, most unprotected had a rainfall less than 1000mm whereas protected pixels had a high proportion of pixels with 1000mm and 1250mm of rainfall. After matching, the distribution of rainfall in unprotected pixels more closely resembled protected pixels. There were more the number of unprotected pixels with a slope that ranged from 0-10% and the highest slope for unprotected pixels was around 60%. Protected pixels had a slope that ranged between 0 and 60% with more protected pixels between 20-40% than unprotected pixels. Matching removed most of the low slope unprotected pixels to produce a similar distribution. Before matching, distance to roads for unprotected pixels had the highest proportion at 0.00 with nearly none of the unprotected pixels exceeding 0.2. Matching produced a sample in which most unprotected pixels were between 0.0 and 0.5. Between treatment groups, the distributions for distance to watercourses were similar before matching, although there were slightly more unprotected pixels between 0.0 and 0.1. Matching produced a sample with more unprotected pixels closer to watercourses, slightly reducing the peak observed before matching.

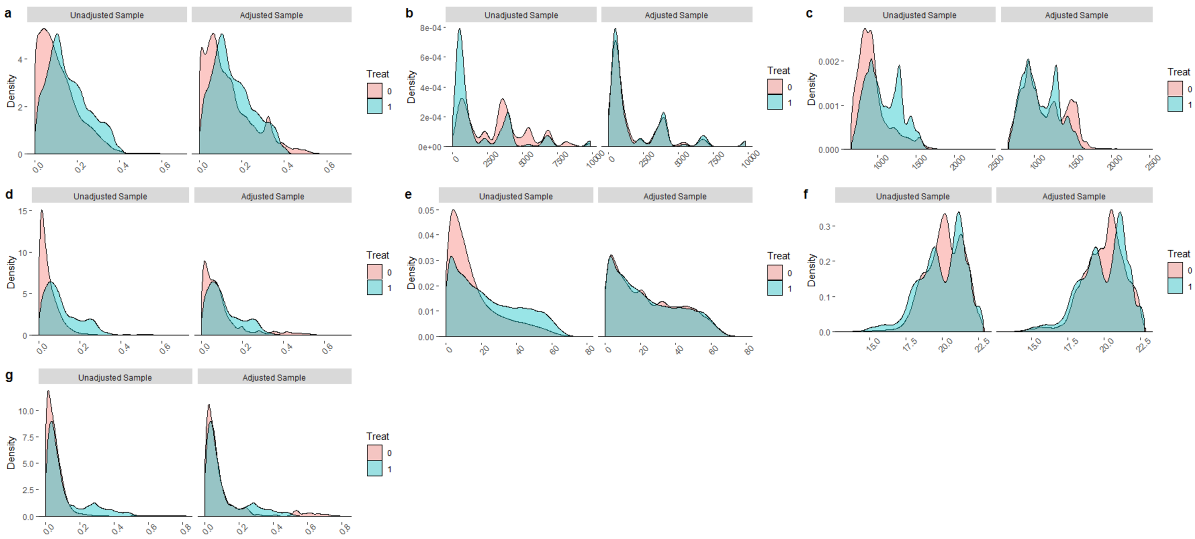


Figure A3-20: Co-variate distribution by treatment category for Southeast Queensland. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= grass biomass, C = Rainfall, D = Distance to major roads, E = Slope, and F= Temperature, G = Distance to major watercourses.

Wet Tropics

Before matching the (unadjusted) co-variates with notable distributional differences were: built-up areas, roads slope, and temperature. Most protected pixels were 0.1 dd from built-up areas, or between 0.2 and 0.4dd. In contract, most unprotected pixels are less than 0.1. The distribution of grazing capacity was highly varied both before and after matching for protected and unprotected pixels; however, pixels with a grazing capacity greater than 500kg/ha were only unprotected. Pixels with a high grazing capacity were removed after matching. Before matching, rainfall distributions. This means that the majority of both protected and unprotected pixels had a high average annual rainfall; however, there was a slight difference in the distribution of these values. Before matching, unprotected pixels tended to be very close to roads where the majority had a distance less than 0.1 dd. In contrast, there was an even distribution in the distance from roads for protected pixels. The majority of unprotected pixels had a slope of less than 10%, and the highest slope for unprotected pixels was around 20%. Protected pixels had a slope that ranged between 0 and 60% with more protected pixels between 20-40% than unprotected pixels. Matching removed most of the low slope unprotected pixels to produce a similar distribution. Distance to watercourses had similar distributions matching except that more unprotected pixels were between 0.0 and 0.05 dd.

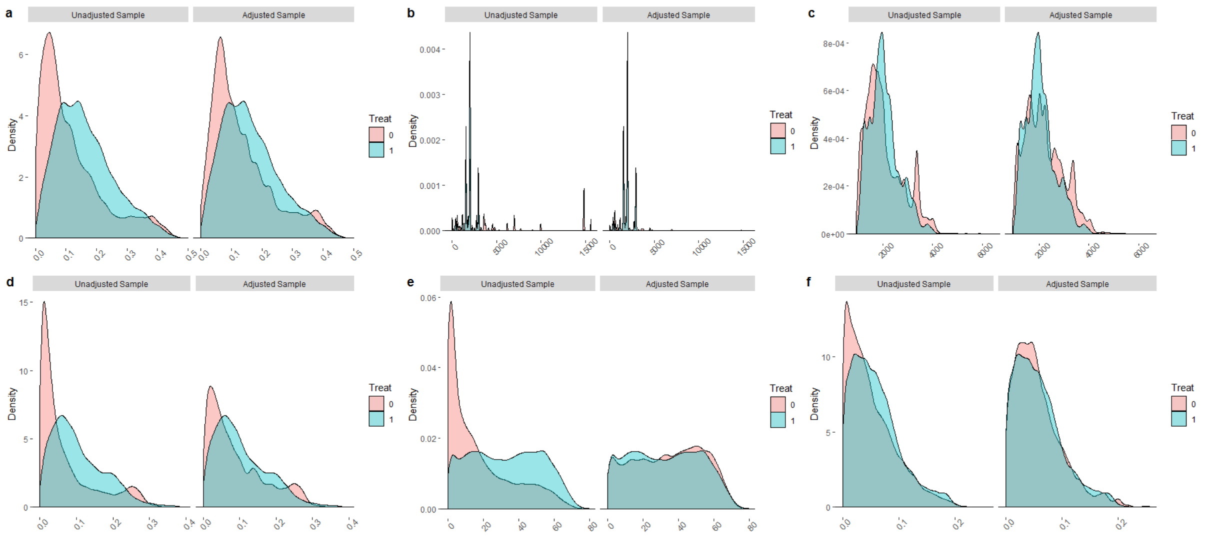


Figure A3-21: Co-variate distribution by treatment category for Wet Tropics. Unprotected pixels are shown in red and protected pixels are shown in blue. A = Distance to Built-up areas, B= Graze, C = Rainfall, D = Distance to major roads, E = Slope, and F = Distance to major watercourses.

A3.5 Sensitivity Analysis

Higher gamma values indicate that the analysis is robust to the effects of an unobserved co-variate. The lowest significant gamma (Γ) value observed was for the New England Tablelands (1.2), and the highest value observed was 11.72 in the Einasleigh Uplands. High values of Γ are associated with robust estimates, and the interpretation is that the odds ratio would have to change by a factor of 1.2 (New England Tablelands) or 11.72 (Einasleigh Uplands) to render the estimates statistically insignificant at a level of 0.05 (Rasolofoson et al. 2015a). I conclude that our results are highly robust to hidden bias (Keele 2010).

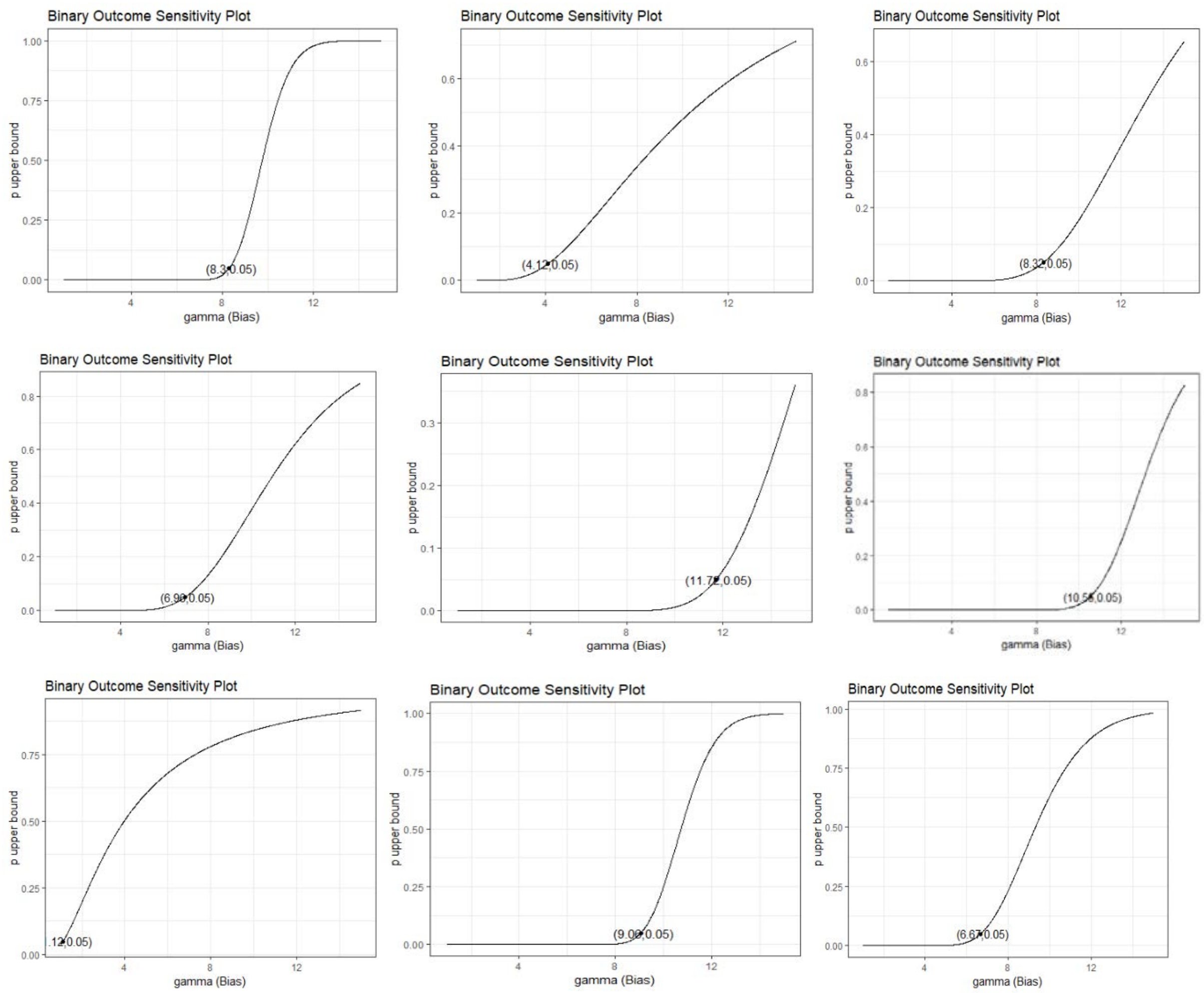


Figure A3-22: Sensitivity analysis per bioregion. Bioregions are presented alphabetically: Brigalow Belt, Central Queensland Coast, Cape York, Desert Uplands, Einasleigh Uplands, Mulga Lands, New England Tablelands, Southeast Queensland and the Wet Tropics.

A3.6 Spatial Autocorrelation

I produced bubble plots in Cobalt to assess the presence of residual spatial autocorrelation. Here the size of the bubble corresponds to the size of the residual and the colour corresponds to either a positive (black) or negative (grey) value. If spatial autocorrelation were present, I would see a pattern in the size, colour or location of the residuals. Based on this visual inspection, I concluded that residual spatial autocorrelation is unlikely to be influencing most of the bioregions, but that it may be affecting Cape York, the Desert Uplands, and the New England Tablelands.

Brigalow Belt

In the Brigalow Belt, there were clusters of positive residuals in central and southeastern portions of the bioregion. Positive residuals ranged from 1 and 4.3, where the majority were between 2.5 and 4. Negative residuals ranged from 0 to –2.15 but tended to be approximately -1. We confirm that there is an effect of spatial autocorrelation in the matched dataset (Moran's I = -0.00085, p<0.05) and in the random dataset (Moran's I = -0.0011, p<0.05).

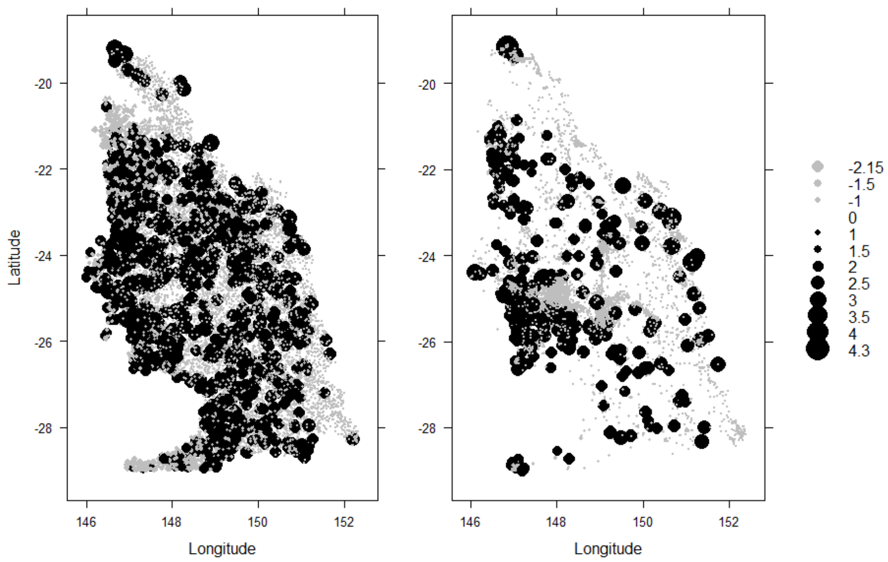


Figure A3-23: Bubble plot (n = 10,000) investigating spatial autocorrelation before (left, Moran's I = -0.0011, p = 3.60*E-60) and after (right Moran's I = -0.00085, p =0.00) matching in the Brigalow Belt. The size of the bubbles corresponds to the size of the residuals from a logistic regression model. This model has the formula "cleared~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive or negative.

Cape York

In Cape York, the majority of residuals were negative with a few positive residuals scattered across the bioregion. Positive residuals ranged from 1 and 5, where the majority were between 3.5 and 5. Negative residuals ranged from 0 to –1 but tended to be approximately -1. Overall, spatial auto-correlation might be influencing the data in this bioregion. We confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.0004, p<0.05) and in the random dataset Moran's I = -0.0001, p<0.05).

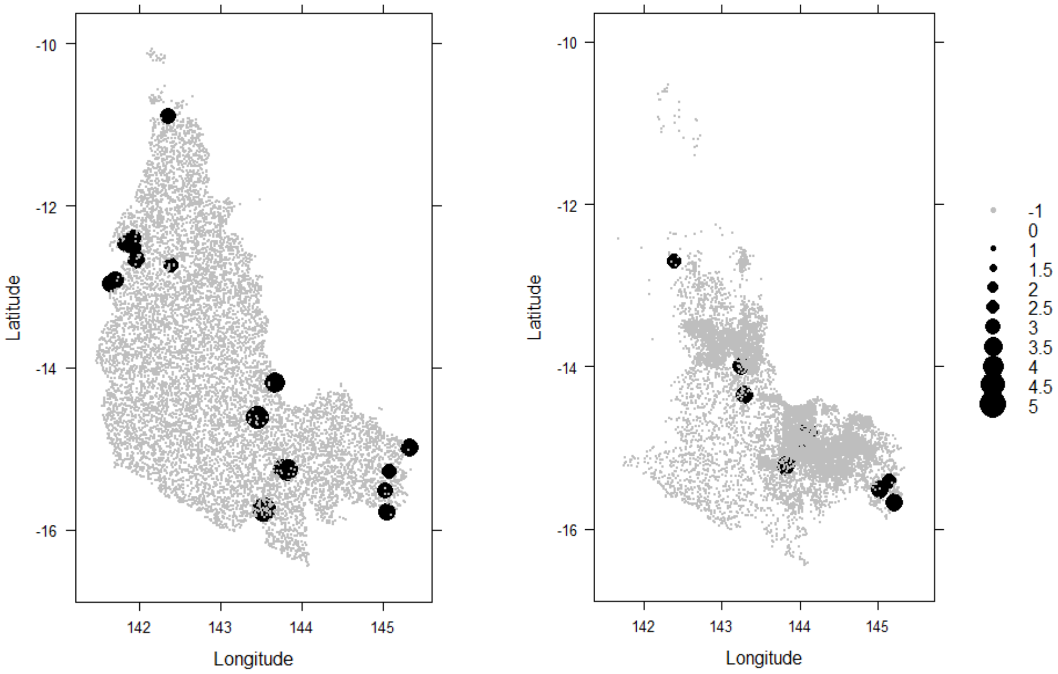


Figure A3-24: Bubble plot investigating spatial autocorrelation before (left Moran's I = -0.0001, p = 0.00) and after matching (right Moran's I = -0.0004, p = 1.2 E-4) in the Cape York, n=10,000. The size of the bubbles corresponds to the size of the residuals from a logistic regression model. This model has the formula "cleared~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Central Queensland Coast

In the Central Queensland Coast, there were clusters of positive residuals in central and southwestern portions of the bioregion. Positive residuals ranged from 1 and 4.5, where the majority were between 3 and 3.5. Negative residuals ranged from 0 to –1 but tended to be approximately -1. Overall, we noted a reduced clustering in the size and distribution of residuals. We confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.00126, p<0.05) and in the random dataset Moran's I = -0.0007, p<0.05).

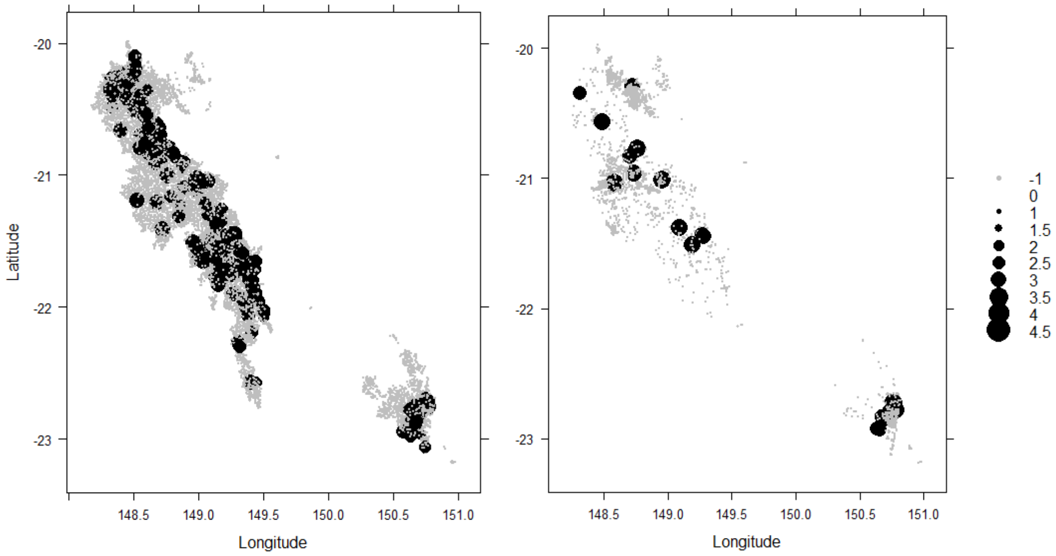


Figure A3-25: Bubble plot investigating spatial autocorrelation before (n=10,000) (left Moran's I = -0.0068, p = 1.05*E-15) and after (n=3,000) (right: Moran's I = -0.0027, p = 1.82*E-16) matching in the Central Queensland Coast. The size of the bubbles corresponds to the size of the residuals from a logistic regression model. This model has the formula "cleared~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Desert Uplands

In Desert Uplands, there were clusters of positive residuals in the northeast, mid-west and southern portions of the bioregion. Positive residuals ranged from 1 and 5, where the majority were between 3 and 3.5. Negative residuals ranged from –1 and –3.5 but tended to be approximately -1. Overall, we noted a reduced clustering and concluded that spatial auto-correlation might be influencing the data in this bioregion, but its effects were reduced by matching. We confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.00126, p<0.05) and in the random dataset Moran's I = -0.001, p<0.05).

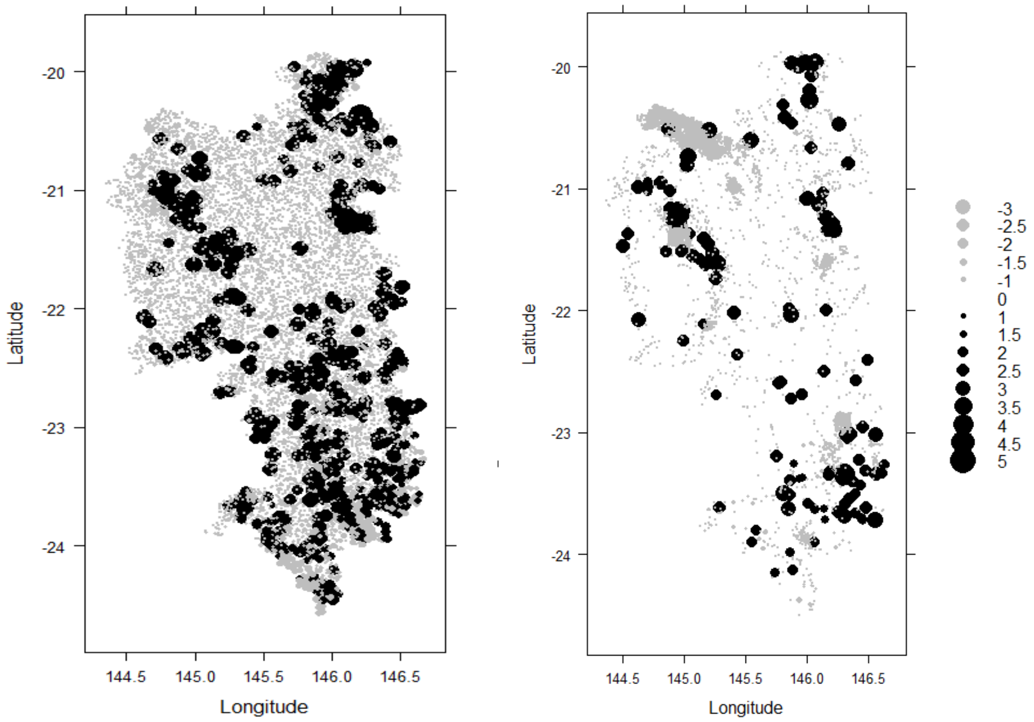


Figure A3-26: Bubble plot investigating spatial autocorrelation before (left Moran's I = -0.0001, p = 7.79*E-43 ,n=10,000) and after (right, Moran's I = -0.000191, p = 1.04*E-72, n = 7,836) matching in the Desert Uplands. The size of the bubbles corresponds to the size of the residuals from a logistic regression model. This model has the formula "cleared~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Einasleigh Uplands

In Einasleigh Uplands, the majority of residuals were negative with a few positive residuals scattered across the mid-eastern portion of the bioregion. As observed in other bioregions, positive residuals tended to be larger (between 6 and 6.5), and negative residuals tended to be -1. We confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.00176, p<0.05) and in the random dataset Moran's I = -0.00156, p<0.05).

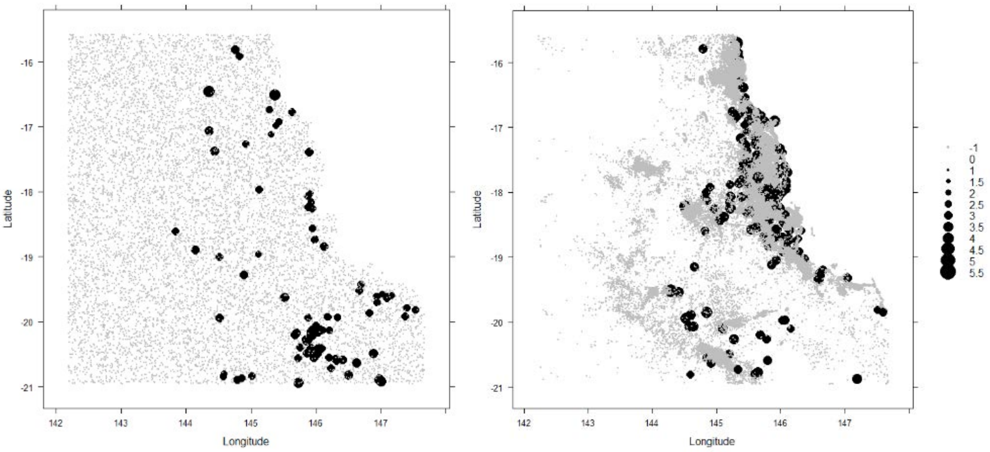


Figure A3-27: Bubble plot investigating spatial autocorrelation before (left Moran's I = -0.00156, p = 9.15.*E-137) and after (right Moran's I = -0.00176, p = 7.36.*E-157) matching in the Einasleigh Uplands (n=10,000). The size of the bubbles corresponds to the size of the residuals from a logistic regression model. This model has the formula "cleared~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Mulga Lands

In Mulga lands positive residuals were clustered in the eastern portion of the bioregion. As observed in other bioregions, positive residuals tended to be larger (between 3.5 and 4) in both the matched and random datasets, and negative residuals were generally between -1 to -1.5. We confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.0006, p<0.05) and in the random dataset, Moran's I = - 0.00075, p<0.05).

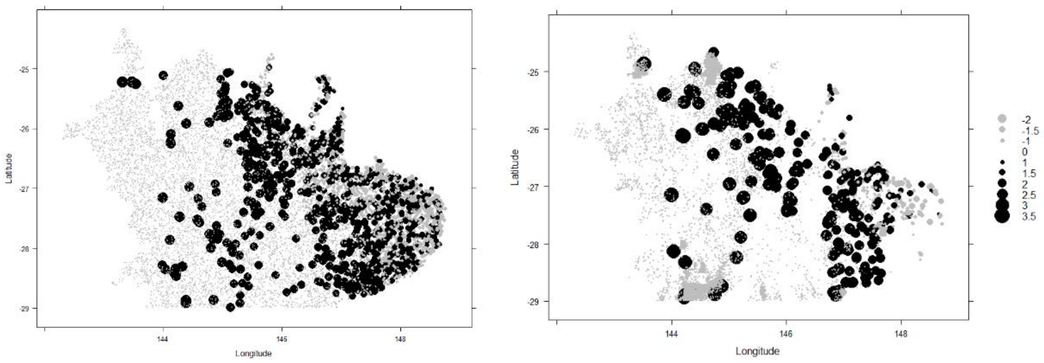


Figure A3-28: Bubble plot investigating spatial autocorrelation before (left Moran's I = -0.00075, p = 5.78*E-28) and after (right Moran's I = -0.0006, p = 2.09*E-16) matching in the Mulga Lands (n=10,000). This model has the formula "cleared ~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

New England Tablelands

The distribution of residuals in the New England Tablelands showed no clear distributional pattern. However, positive residuals tended to be larger (between 3 and 3.5). After matching, the total number of pixels was reduced. I confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.0012, p<0.05) and, but not in the random dataset Moran's I = -0.0010, p>0.05). I caution the interpretation of this result, however, because this bioregion is heavily cleared so much so that clearing is not so much spatially autocorrelated as it is extensive.

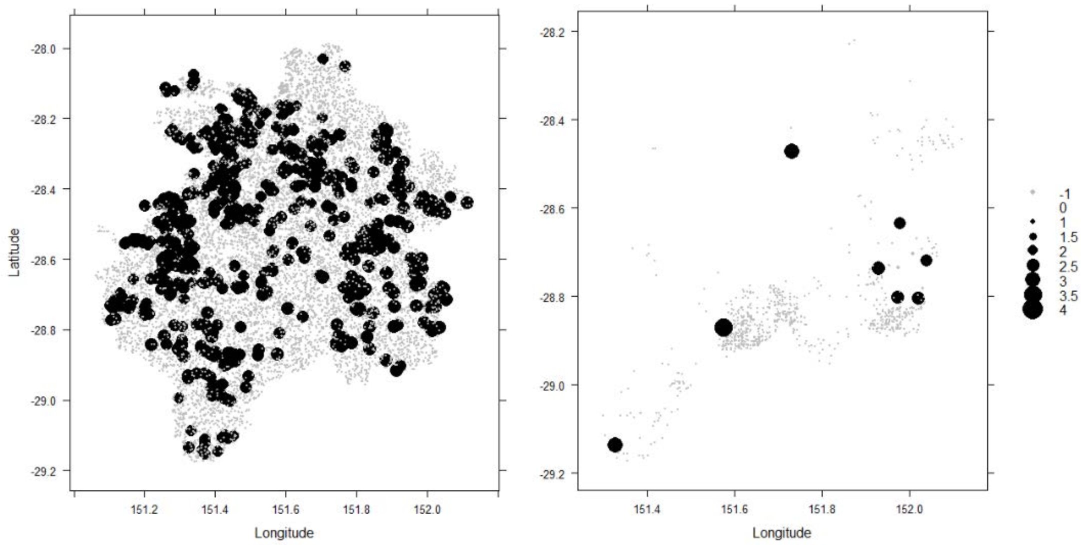


Figure A3-29: Bubble plot investigating spatial autocorrelation before (left, Moran's I = -0.0012, p = 1.89*E-79, n=10,000) and after (right, Moran's I = -0.0010, p = 0.774, n = 782) matching in the New England Tablelands. This model has the formula "cleared ~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Southeast Queensland

In Southeast Queensland, positive residuals clustered in the eastern portion of the bioregion before matching (left), and negative residuals tended to occur on the western side of the bioregion and along Stradbrook Island. Before and after (right) matching, and as observed in other bioregions, most of the positive residuals were between 4 and 4.5 whereas negative residuals were generally around –1. I can confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.00016, p<0.05) and in the random dataset Moran's I = -0.0002, p>0.05).

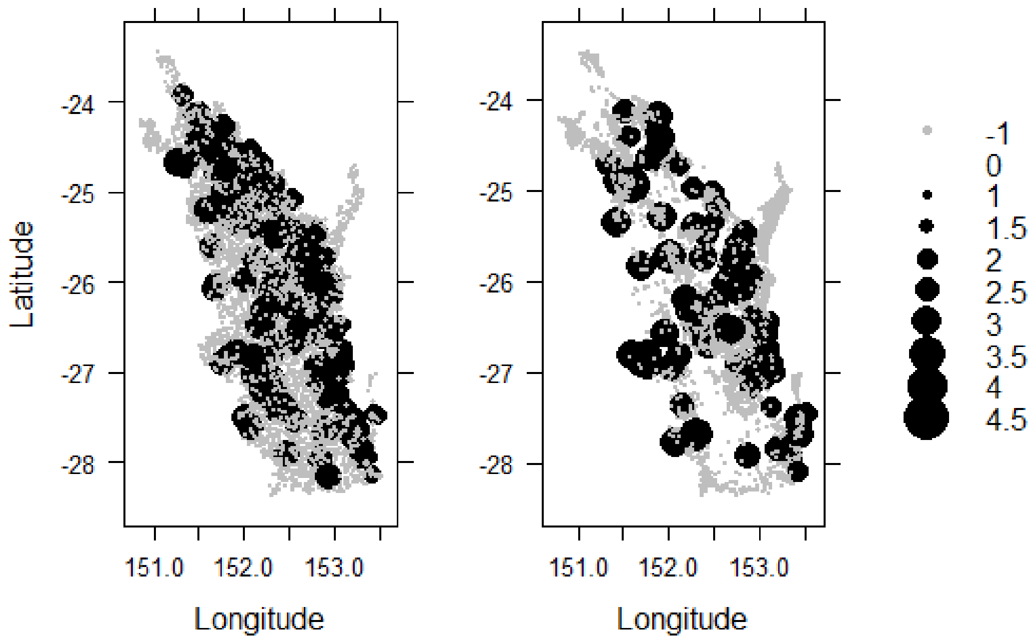


Figure A3-30: Bubble plot investigating spatial autocorrelation before (left, Moran's I = -0.0002, p = 0.167, n=10,000) and after (right, Moran's I = -0.00016, p = 0.398, n = 10000) matching in Southeast Queensland. This model has the formula "cleared ~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

Wet Tropics

In the Wet Tropics, positive residuals clustered in the southeastern portion of the bioregion before matching (left). Before and after (right) matching, and as observed in other bioregions, most of the positive residuals were between 2.5 and 3 whereas negative residuals were generally around

–1. I can confirm that there is an effect of spatial autocorrelation in the matched dataset Moran's I = -0.0007, p<0.05) and in the random dataset Moran's I = - 0.0004, p>0.05).

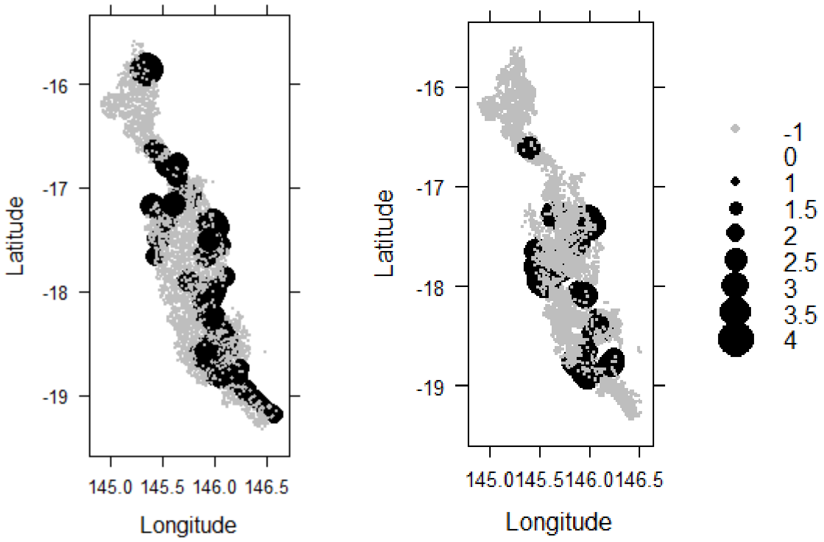


Figure A3-31: Bubble plot investigating spatial autocorrelation before (left, Moran's I = -0.0004, p = 4.71*E-05, n=10,000) and after (right, Moran's I = -0.0007, p = 8.72*E-16, n = 10000) matching in the Wet Tropics. This model has the formula "cleared ~ co-variate1 + co-variate2 + co-variate3…" The colour of the bubble indicates whether or not the residuals are positive (black) or negative (grey).

A3.7 Boxplots and outliers in the ATT estimates

Outliers, or of the 1,000 ATT estimate, values which were above or below the first and third quartile, were present for all bioregions, but most were in the New England Tablelands (Figure 6). This resulted in large variance in the matched ATT estimates (-0.07% to -17.8%). I attribute the cause of this range and ATT outliers to both extensive clearing (McAlpine, Fensham, and Temple-Smith 2002, Science 2019) and the small area under protection in the bioregion (28km^2). I therefore present the mean estimated ATT for New England Tablelands, but caution that outliers influence the mean, possibly decreasing the accuracy of this estimate (**Figure A3-30**).

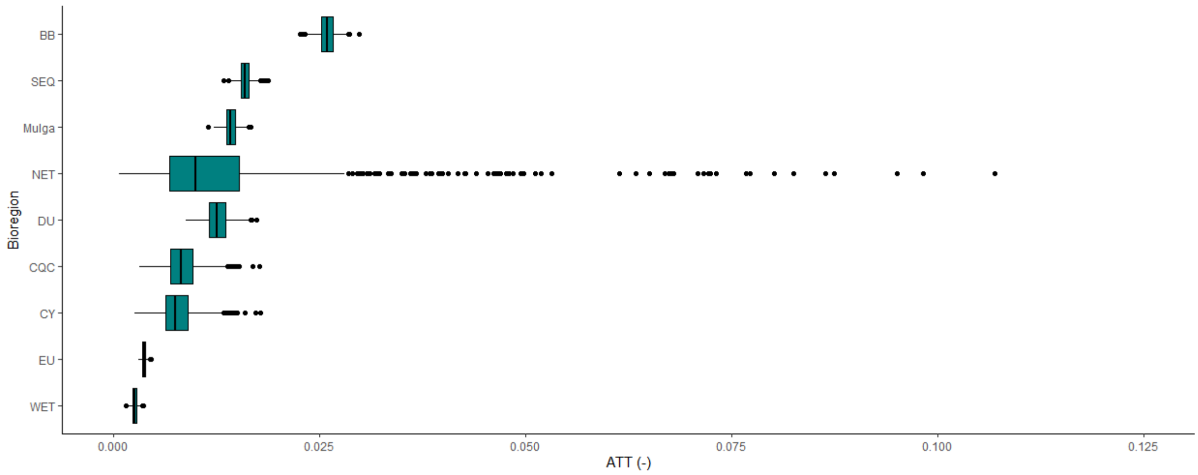


Figure A3-32 : Boxplot of 1,000 simulations for the Average Treatment Effect on the Treated (ATT) after matching.

A3.8 A failure to use statistical matching risks doubling the estimated impact of protection

Protected areas to tend to occur on low capacity land (Joppa and Pfaff 2009, Venter et al. 2018). Owing to this non-random allocation, in this case, as in others (Andam et al. 2008, Geldmann et al. 2013, Vincent 2016), failure to use a robust statistical matching approach substantially overestimated the impact of protected areas - more than tripling the estimated impact of protected areas in some regions.

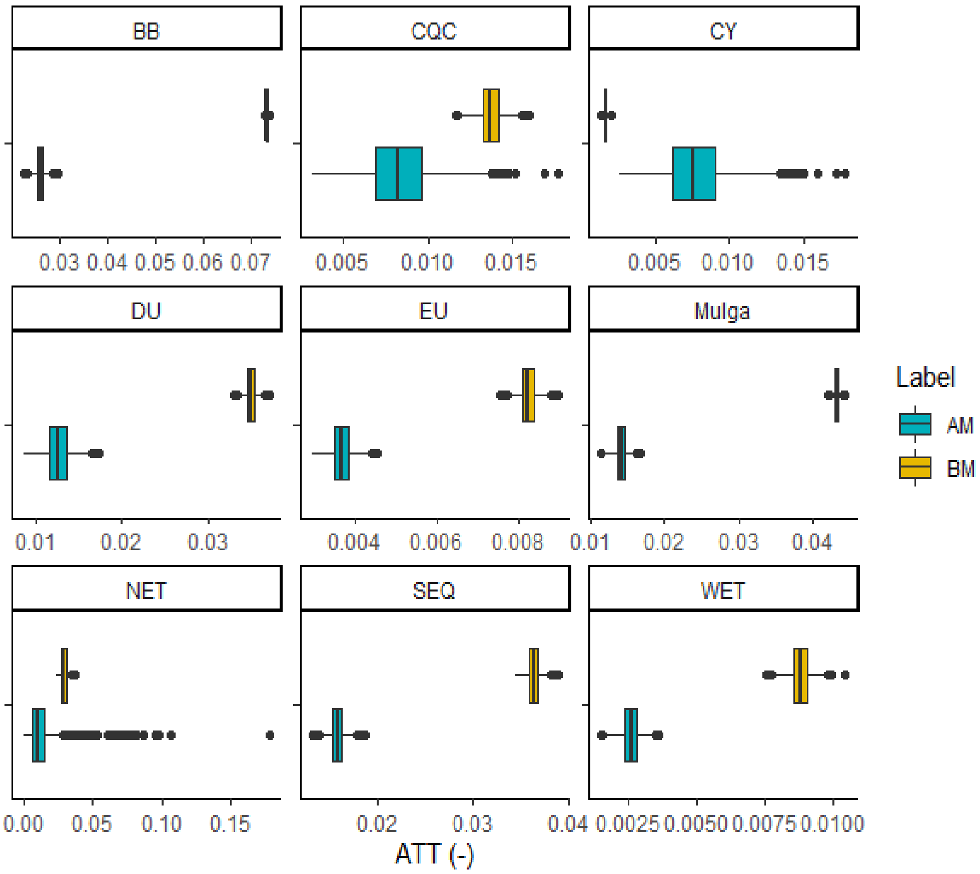


Figure A3-33: Boxplot of 1,000 simulations for the Average Treatment Effect on the Treated (ATT) for each bioregion both before and after matching.

Appendix 4: Supporting information for Chapter 4

A4.1 Methods for creating maps of assessable vegetation

Regulations under the Act enforce performance outcomes. Performance outcomes are stated in guidelines and are enforceable by the regulatory authority. Performance outcomes define the ecological requirements that must be achieved for the clearing to be lawful. This includes the identification of restriction features ("spatial features") relating to the landscape. I identified which spatial features were described in each of the guidelines and their corresponding datasets. These datasets are available for download from the Queensland Government (Supplementary). Ten spatial features were identified and compared across each of the three scenarios (**Figures A4-1-A4-5**).

Table A4-1 Description of data sets used to apply relevant legislative constraints.

Dataset	*Utility*	*Data provider*	*Manipulation*	*Year*
Acid Sulphate Soils	Restriction	DSITIA	Erased from RE Layer	2015
Riparian areas	Restriction	DNRM	Buffered and erased	2015
Wetlands	Restriction	DEHP	Buffered and erased	2015
Slope	Restriction	GeoScience Australia	Derived slopes, erased those deemed inappropriate for clearing	2001
Essential Habitat Map	Restriction	DNRM	Erased from RE layer	2015
Agricultural land audit	Restriction	DNRM	Selected classification A-B (high agricultural suitability) and intersected with "available to clear."	2013
Regional Ecosystem	Restriction	DISTI	Selected appropriate RE Layers	2014
Protected areas	Restriction	DEHP	Erased from available for clearing layer	2015
EPBC protected regional ecosystems	Restriction	DEHP	Erased from available for clearing layer	2015
Ramsar Wetlands	Restriction	DEHP	Erased from available for clearing layer	2014
Dominate Soils	Restriction	DERM	Selected soils considered stable, unstable and very unstable	2007

A4.2 Spatial analysis

Each of the spatial features was described with spatially-explicit criteria (**Figure: 4-1**, main text). First, I identified all spatially explicit criteria for the spatial features described above. Then I removed from the regional ecosystem layer all features prohibited from clearing. This produced a single potential clearing layer for each purpose, each scenario, and each vegetation management category. For example, the *strict* scenario guideline for clearing for fodder harvesting on remnant vegetation stated that no clearing could occur within 200 m of regulated wetlands. In this case, we created a 200 m buffer around regulated wetlands with ArcGIS 10.2.2 (ESRI 2014) and erased the buffered areas from the potential clearing layer.

As described in the main text, clearing for agriculture, irrigated agriculture, and grazing occur within the same guideline, but, because they require different levels of soil arability, I classified them as separate clearing purposes. The spatially explicit criteria for these two purposes are identical except that, unlike grazing, agriculture development on arable soils must demonstrate soil suitability (arability). I performed an additional step to identify areas that met this arability requirement and could be cleared for agriculture. I applied all spatially explicit criteria in this guideline and then created a copied layer restricted to areas identified as having soil suitable for agricultural development ((Department of Agriculture and Fisheries 2014).

A4.2 Comparative summaries

In this section, I consider each scenario and then describe the overall changes to clearing guidelines. I do this by comparing each time step to the previous one (*ie* modern compared to relaxed and relaxed compared to strict). I then describe the implications of the identified changes in terms of increased, decreased or no change in the extent of the available clearing.

Clearing for agriculture

Clearing remnant vegetation to maintain the operational efficiency of existing agricultural areas was not permitted in the *strict* scenario. In the *relaxed* scenario, clearing that was compliant with the guidelines was termed "self-assessable." That is, if the proponent was able to meet the requirements of the guideline, then notification of clearing to the department was not required. Clearing in this scenario was limited to 5 hectares or 10% of the existing cropped area (for a maximum of 100 hectares). It had to occur within or adjacent to existing cropped areas. It was furthermore limited to areas of similar soil and slope (between 3-10% depending on the type of cultivation) to the existing cropped area. Clearing could not occur on essential habitat or, depending on the size and location of the stream, between 10-100m. Clearing could occur on endangered or of concern regional ecosystems so long as an exchange area (**Glossary)** is provided. Furthermore, the clearing guidelines stipulate that clearing must not cause accelerated soil erosion or the release of acid sulphate soil. To achieve this, proponents must not clear in landzones 1,2, or 3 and must take reasonable steps the avoid the disturbance of the soil to a depth with will activate acid sulphate soils or expose the water table.

In the *modern* scenario, the proponent is required to notify the Department of Natural Resources Mines and Energy (DNRME) before the clearing commences. Clearing for agriculture can only occur to establish irrigation systems or to straighten the edges or margins of existing cropped areas. Even then, land clearing is limited to a total of five hectares of remnant vegetation per property. Slope limits were not mentioned in this guideline nor were restrictions on specific regional ecosystems. Land clearing was not permitted essential habitat or, unlike the *relaxed* scenario, in endangered or of concern regional ecosystems. Land clearing was not permitted within 100m of any wetland or within, depending on the size, between 10-50m of streams. Furthermore, clearing is not permitted within 100m of salinity expression areas or on landzones 1,2 or 3 if the elevation is less than five metres above sea level.

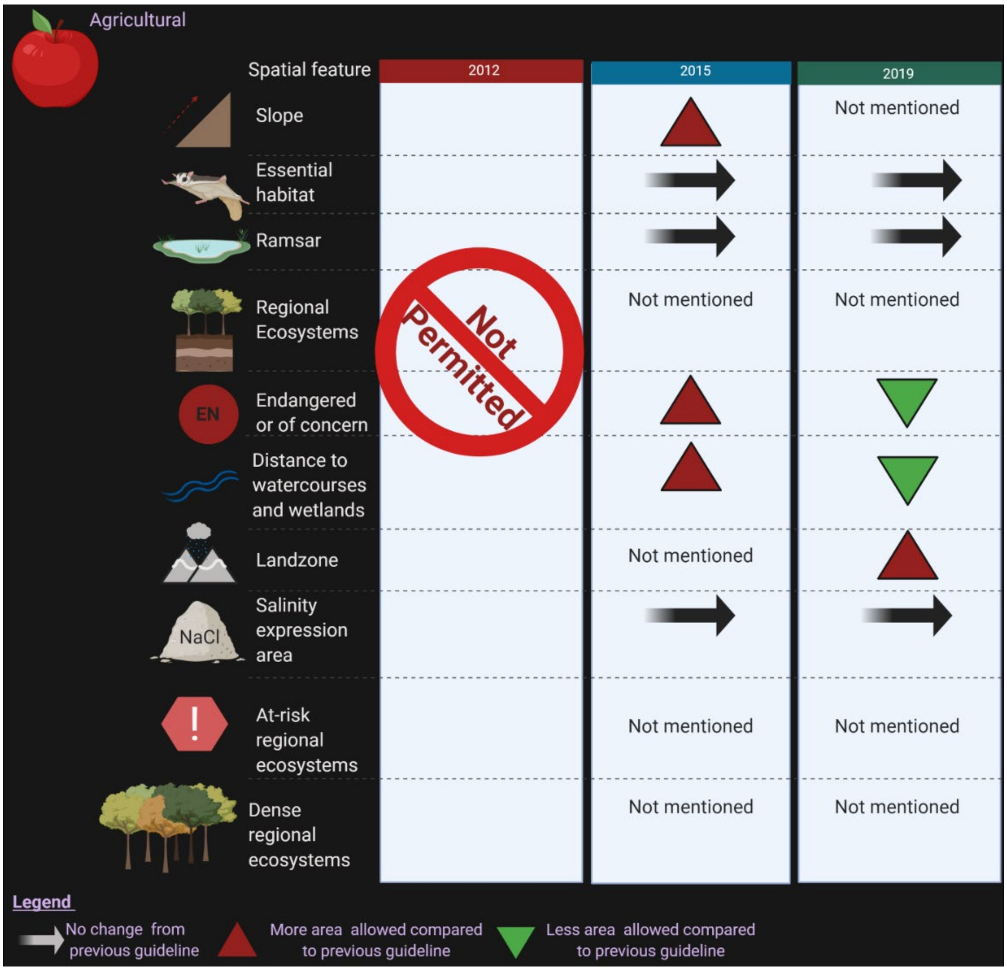


Figure A4-1: Comparison of the landscape and biophysical features discussed in agricultural clearing guidelines for each of the three scenarios. The first panel refers to the clearing guidelines in the *strict* scenario. In this panel, I describe the criteria relevant to each feature in the guideline. The middle panel shows the effect of any change from the *strict* guideline (*ie* from 2012) to the *relaxed* (*ie* from 2015). The final panel demonstrates the effect of any changes from the *relaxed* scenario to the *modern* scenario.

Clearing for encroachment

In the *strict* scenario, clearing for the purpose of removing encroaching vegetation was only permitted in the Brigalow Belt, Cape York Peninsula, Channel Country, Gulf Plains, Einasleigh Uplands, Desert Uplands, Northwest Highlands, Mitchell Grass Downs, Mulga Lands bioregions. Dependant on the soil stability, the clearing was limited to slopes between 1-10%. Clearing could not occur in essential habitat or within 200m of Ramsar wetlands. The clearing was limited to ten specific regional ecosystems and was not permitted on any endangered or of concern regional ecosystems. Depending on the size of the stream, clearing could not occur within 50-200m of the watercourse. The clearing was not permitted on landzones 1, 2 or 3 if the proposed area was 5 metres below sea-level unless clearing was carried out in compliance with *State Planning Policy 2/02 Guideline: Planning and Managing Development involving Acid Sulfate Soils* and *Queensland Acid Sulfate Soil Technical Manual*. At-risk and dense regional ecosystems were not mentioned for this clearing purpose.

Clearing remnant vegetation for the purpose of managing encroaching vegetation in the *relaxed* scenario was, again, self-assessable. That is, clearing, so long as it complied with the guideline, did not require departmental assessment. Compliance with guidelines could be demonstrated if clearing was not proposed on essential habitat areas or on slopes greater than 5%. The clearing was only allowed in 23 regional ecosystems, and could not occur within 50m of wetlands or within 10-20m of streams. In Cape York and the Gulf of Carpentaria, the clearing was not permitted on landzones 1,2 or 3 which is less than 5 metres below sea level. Ramsar wetlands were not mentioned in the relaxed guideline for encroachment clearing. However, clearing is regulated under the Federal *Environmental Protection and Biodiversity Conservation Act, 1999*, and this may be why it is not mentioned in this guideline.

Clearing remnant vegetation for the purpose of managing encroaching vegetation in the *modern* scenario required the clearing proponent to notify the department before the commencement of clearing and must include historical and recent satellite imagery or photographs which demonstrate that encroachment is occurring. Clearing in this scenario is limited to 400 hectares per property and must not happen on slopes higher than 5%. Essential habitat was not mentioned in this clearing guideline nor were Ramsar wetlands. The clearing is limited to the 19 regional ecosystems specified in the guideline. Of concern and endangered regional ecosystems were not mentioned. The clearing was not permitted within 20m of wetlands or (depending on the size) within 10-20m of a watercourse. Unlike previous guidelines, the *modern* guideline specified that clearing must retain mature and habitat trees. It was further specified that clearing could not occur on landzone 1 or within 100m of salinity expression areas. Clearing in landzone 3 at less than 5metres above sea level must not result in the disturbance of soil to a depth greater than 30cm.

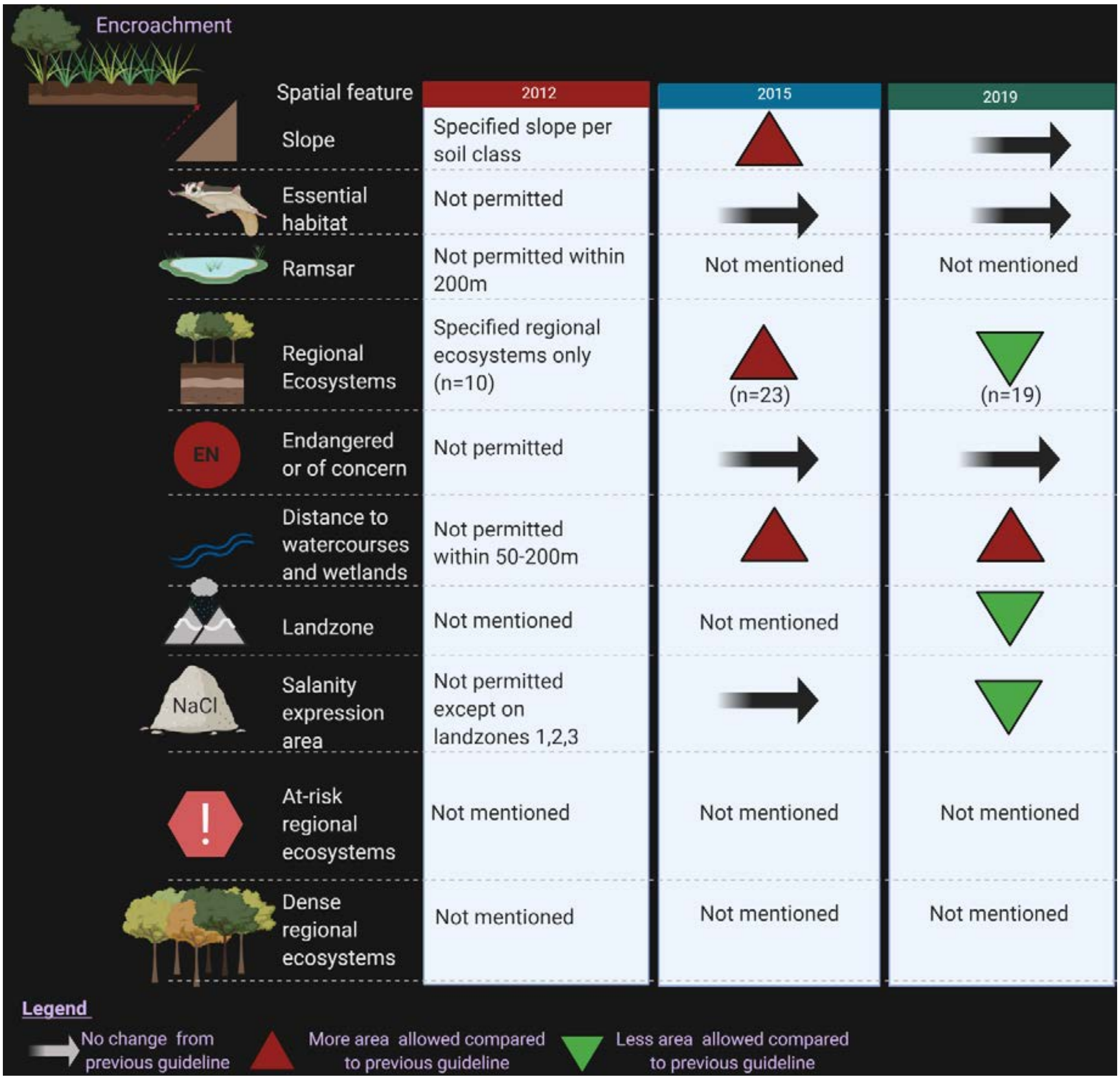


Figure A4-2: Comparison of the landscape and biophysical features in encroachment clearing guidelines for each of the three scenarios. The first panel refers to the clearing guidelines in the *strict* scenario. In this panel, I describe the criteria relevant to each feature in the guideline. The middle panel shows the effect of any change from the *strict* guideline (*ie* from 2012) to the *relaxed* (*ie* from 2015). The final panel demonstrates the effect of any changes from the *relaxed* scenario to the *modern* scenario.

Clearing for an extractive industry (mining)

In the *strict* scenario, clearing to establish an extractive industry was regulated in two ways: for areas in a key resource area and areas not within a key resource area. Key resource areas were specific locations defined in the *State Planning Policy: Protection of Extractive Resources*. With regards to each spatial feature, the clearing guidelines required that clearing "maintain the current extent" of assessable vegetation. The slope of the land is not mentioned. Clearing is not permitted in essential habitat areas, within 200m of Ramsar wetlands or within 100m of any other wetland. There are no specific restrictions on regional ecosystems except that clearing is not permitted in any of the at-risk regional ecosystems defined in the guideline unless the clearing is less than 2 hectares (n=55). Clearing was permitted in of concern or endangered regional ecosystems listed in the guidelines as dense regional ecosystems. For those that are not listed, clearing is restricted to 10m wide or 0.5 hectares. Clearing was not permitted within 25-200m of watercourses (depending on the size and the bioregion). Clearing was not permitted on landzones 1, 2 or 3 if the proposed area was 5 metres below sea-level unless clearing was carried out in compliance with *State Planning Policy 2/02 Guideline: Planning and Managing Development involving Acid Sulfate Soils* and *Queensland Acid Sulfate Soil Technical Manual*.

Clearing remnant vegetation to establish an extractive industry in the *relaxed* scenario was, again, self-assessable. It was clearly stated that clearing is not permitted on remnant vegetation unless there is no reasonable alternative site. Constraints regarding the slope of the land were not mentioned in the relaxed scenario. Clearing is not permitted in essential habitat nor within 100m of wetlands though Ramsar wetlands are not explicitly mentioned. Clearing is permitted on endangered or of concern regional ecosystems with limitations. These limitations refer to the structure category of the regional ecosystem (dense and mid-dense, sparse and very sparse, or grassland). Depending on the structure category between 0.5-2 hectares of clearing is permitted. Furthermore, depending on the area (coast vs non-coastal) and the size of the stream, clearing is not permitted within 10-100m of watercourses. Clearing was not allowed on landzones 1, 2 or 3 if the proposed area was 5 metres below sea-level, and clearing was not permitted on acid sulphate soils.

Clearing remnant vegetation for extractive industry in the *modern* scenario required the proponent to notify the department before the commencement of clearing. The slope was not specified in this guideline. Unlike previous codes, clearing was not expressly prohibited in this guideline. Instead, it instructed proponents to avoid and minimise clearing in essential habitat and of habitat trees. The clearing was not permitted within 100m of wetlands though Rasmar wetlands are not explicitly mentioned. As per the *relaxed* scenario, clearing is permitted on endangered or of concern regional ecosystems with structure category limitations (between 0.5-

2 hectares). Clearing, again, was not allowed on landzones 1,2 or 3 where elevation is less than 5metres below sea level unless clearing complies with *State Planning Policy* or *Soil Management Guidelines in the Queensland Acid Sulfate Soil Technical Manual* or within 100m of salinity expression areas.

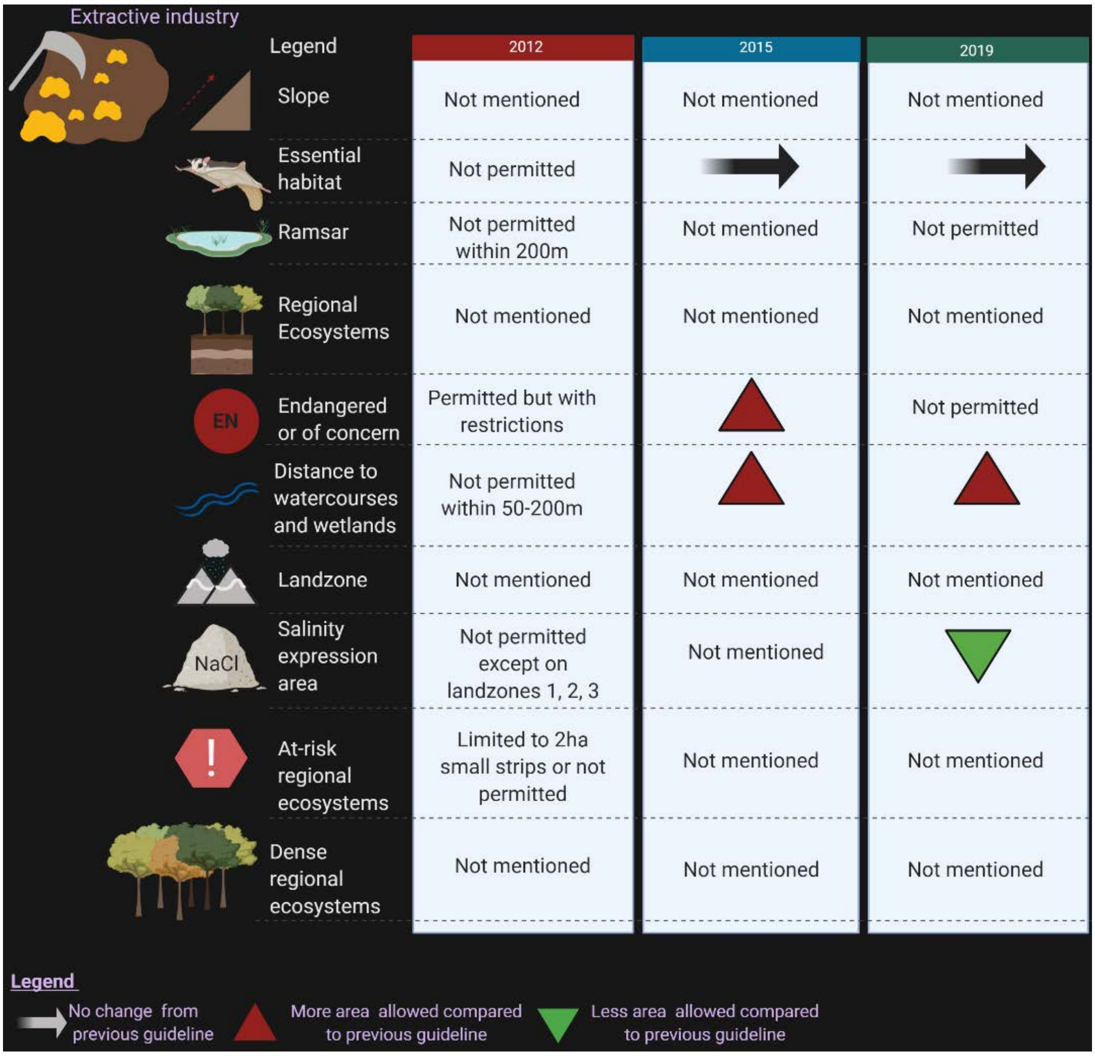


Figure A4-3 A comparison of the landscape and biophysical features in extractive industry clearing guidelines for each of the three scenarios. The first panel refers to the clearing guidelines in the *strict* scenario. In this panel, I describe the criteria relevant to each feature in the guideline. The middle panel shows the effect of any change from the *strict* guideline (*ie* from 2012) to the *relaxed* (*ie* from 2015). The final panel demonstrates the impact of any changes from the *relaxed* scenario to the *modern* scenario.

Clearing for fodder harvesting

In the *strict* scenario, clearing to harvest fodder could only occur in the Mulga Lands bioregion and nine subregions, the Southern Downs, Werlbone High, Moonie-Barwon Interfluve, and Balonne-Culgoa Fan, the Goneaway Tablelands, Copper Plains and the Nuccundra Slopes. Fodder harvesting was further limited to no more than 30% of a property. Slope was limited to areas with a less than 5% slope and could not occur in areas of essential habitat. Clearing could not occur within 200m of Ramsar wetlands or 100m of other wetlands. Clearing for fodder harvesting was further limited to 32 specified regional ecosystems and was wholly prohibited in endangered or of concern regional ecosystems.

Furthermore, the guideline specifies that clearing should not remove more than 55% of the predominant canopy over a nine-hectare area nor diminish the range of species within the regional ecosystem. Depending on the size, clearing could not occur within 200-50m. Clearing could not occur within 200m of salinity expression areas. The relaxed guidelines didn't mention at-risk and dense regional ecosystems. A failure to mention these categories is unlikely to have increased non-assessable vegetation because clearing was limited to the regions described above.

Clearing remnant vegetation for fodder harvesting in the *relaxed* scenario was, again, self-assessable. There were no specifications regarding the slope of the land. Fodder harvesting was not permitted essential habitat areas. There were more regional ecosystems available for clearing (n=49), and *relaxed* guidelines permitted clearing four of-concern regional ecosystems. The guidelines didn't specify restrictions regarding the removal of the predominant canopy. Again, there was no mention of Ramsar wetlands, but, in general, the guidelines prohibited clearing within 100m of wetlands. Depending on the size of the proposed clearing, the guidelines prevented clearing within 10-20m of watercourses. The guidelines made no specific mention of landzones but prohibited clearing d within 200m of salinity expression areas. Compared to the strict guideline, this restriction decreased the amount of area exposed to clearing.

Unlike the *relaxed* guideline, the *modern* guideline required landholders to notify the department of their intent to clear. Clearing was limited to 500 hectares per property. As per the *strict* scenario, clearing was once again not permitted on slopes higher than five per cent. The modern guidelines did not mention Ramar wetlands, but clearing was generally not allowed within 50m of wetlands. The modern guidelines permitted clearing for fodder harvesting on 45 regional ecosystems, and selective collection (or the removal of just a few trees) was permitted on three of concern regional ecosystems. In the previous two guidelines, the defining bank of a watercourse determined how closely a proponent could clear to a watercourse. The type of clearing dictated the defining bank (*ie* clearing in strips or clearing in bulk areas; strip or block harvesting). The guidelines clearly state that clearing is not allowed on regional ecosystems which occur on landzone seven or are within 100m of salinity expression areas. Overall, the restrictions for fodder clearing in the *modern* guidelines reinstated some of the requirements of the *strict* scenario representing an overall decrease in the amount of vegetation which can be cleared for fodder harvesting.

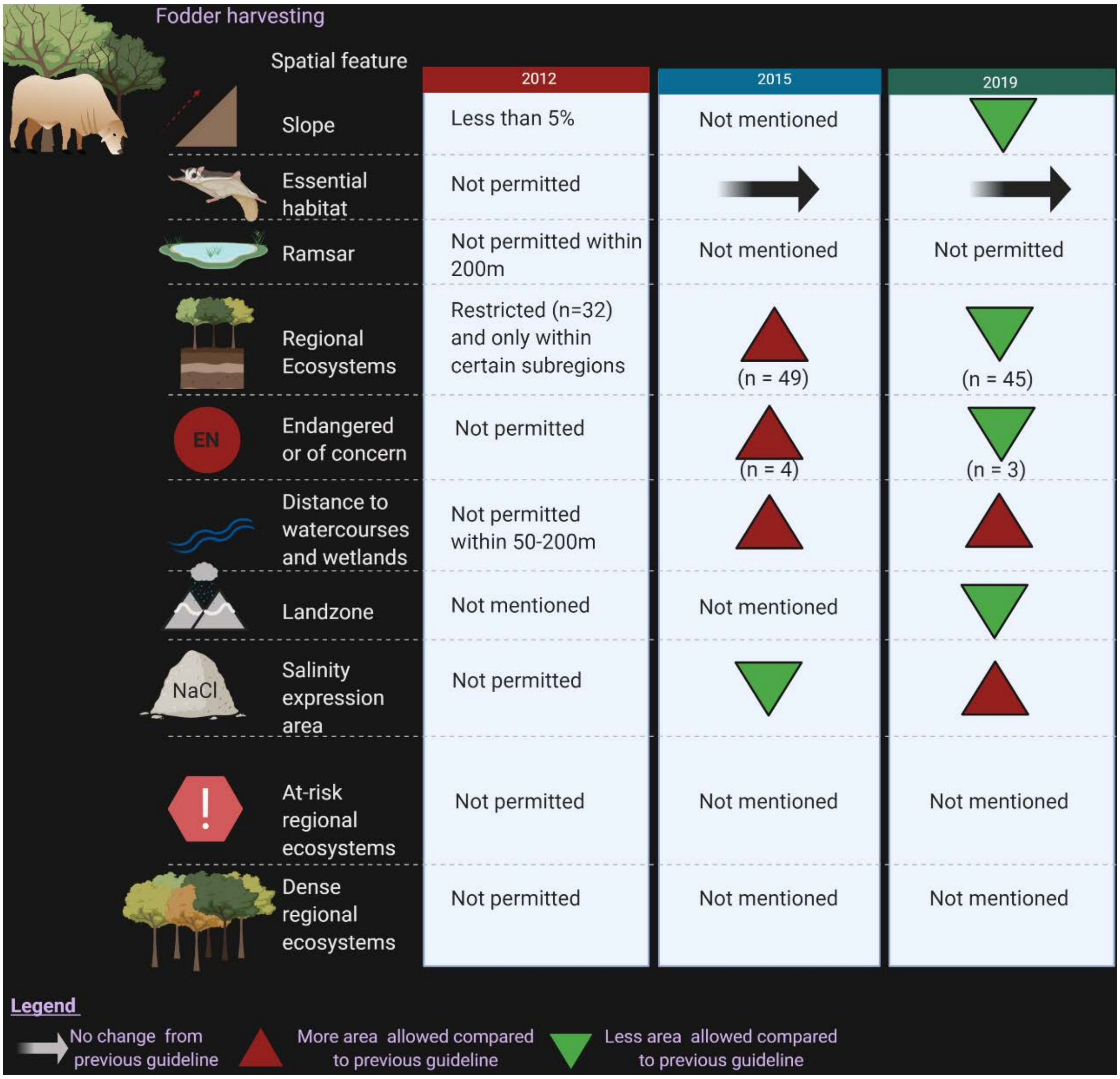


Figure A4-4 Comparison of the landscape and biophysical features in fodder harvesting clearing guidelines for each of the three scenarios. The first panel refers to the clearing guidelines in the *strict* scenario. In this panel, I describe the criteria relevant to each feature in the guideline. The middle panel shows the effect of any change from the *strict* guideline (*ie* from 2012) to the *relaxed* (*ie* from 2015). The final panel demonstrates the effect of any changes from the *relaxed* scenario to the *modern* scenario.

Clearing for thinning

In the *strict* scenario, proponents of clearing were required to demonstrate that vegetation is thickening by providing the department with satellite imagery which shows a 30% increase in the woody species crown cover. Clearing was permitted in all bioregions, but not clearing was not permitted within 200m of Ramsar wetlands or 100m within of other wetlands. Clearing was expressly prohibited in 439 regional ecosystems, and mechanical clearing was forbidden in a further 190 regional ecosystems. Given these limitations, clearing was not permitted on of concern or endangered regional ecosystem, though this was not expressly stated. Clearing was not permitted within 200m of Ramsar wetlands or 100m of other wetlands. Watercourses were not mentioned in the *strict* clearing guidelines. Clearing was not permitted on landzones 1, 2 or 3 if the area was 5m below sea level. Unlike previous codes, clearing in salinity expression areas was not mentioned nor were at-risk or dense regional ecosystems.

In the *relaxed* scenario, there were three regional guidelines for thinning vegetation. In each of the three guidelines, clearing was not permitted on slopes greater than 10% nor was it permitted in areas that are essential habitat. Ramsar wetlands were not mentioned, but clearing is not permitted within 20m of wetlands. Clearing was permitted on 324 regional ecosystems and, for each regional ecosystem, the guidelines specified the number of trees per hectare to retain. Unlike previous guidelines, *relaxed* guideline further specified the method of clearing per regional ecosystem where a proponent may clear trees and shrubs, only shrubs or by burning. Within each guideline, there were also specific instructions on how much ground cover vegetation must be retained (typically around 50%), the buffer size around mature or habitat trees (typically 5metres), and how many immature trees needed to preserved (at least 50%). Although these guidelines introduced such specific restrictions that were not present in the previous guidelines, the buffer size or proximity to wetlands and watercourses was reduced to 10-20m *relaxed* scenario. Landzones were not mentioned nor were salinity expression areas or at-risk or dense vegetation communities. Overall, the guidelines allowed for a reduced amount of native vegetation to be cleared for thinning. Clearing for thinning was not a relevant clearing purpose in the *modern* scenario.

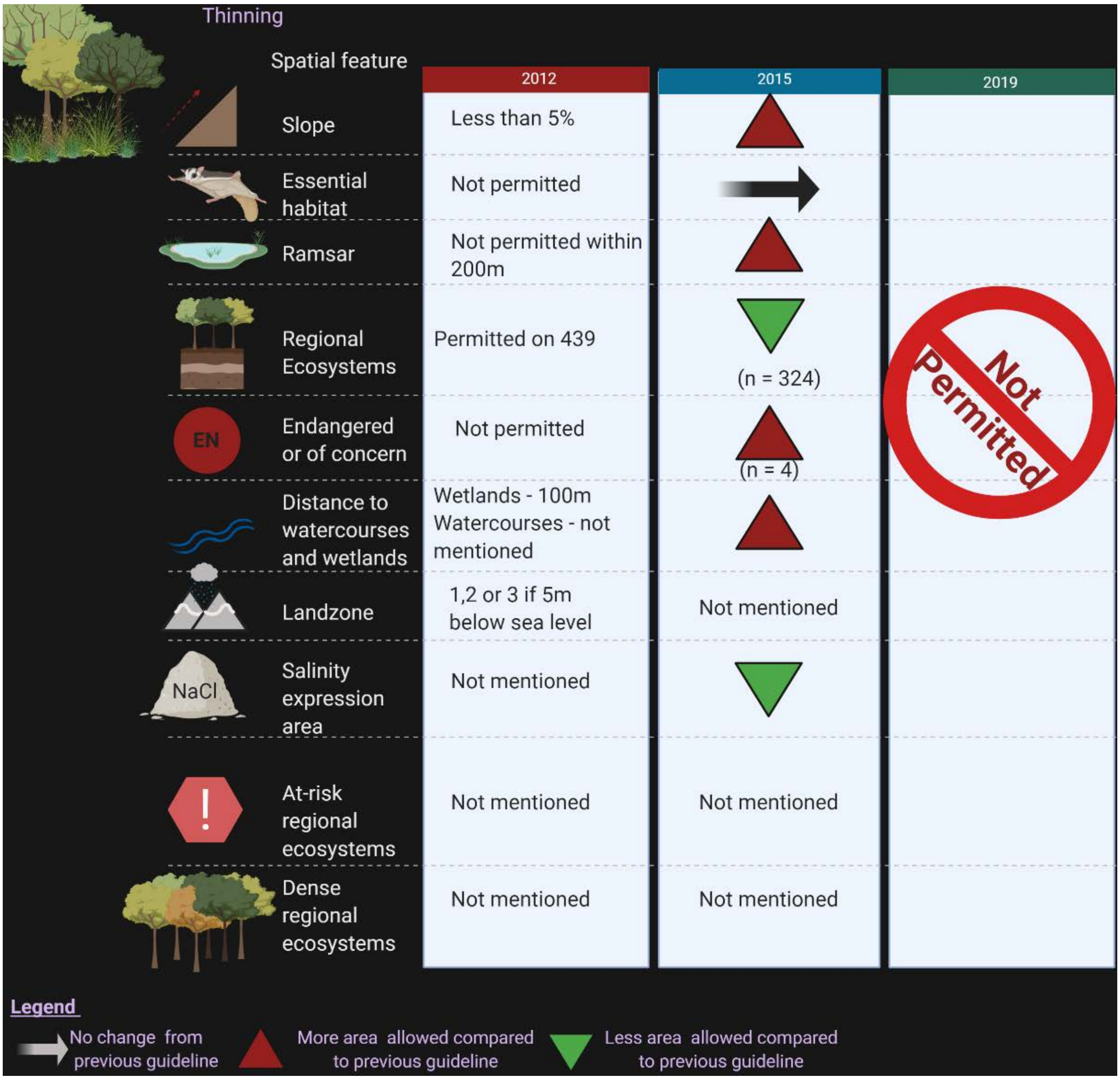
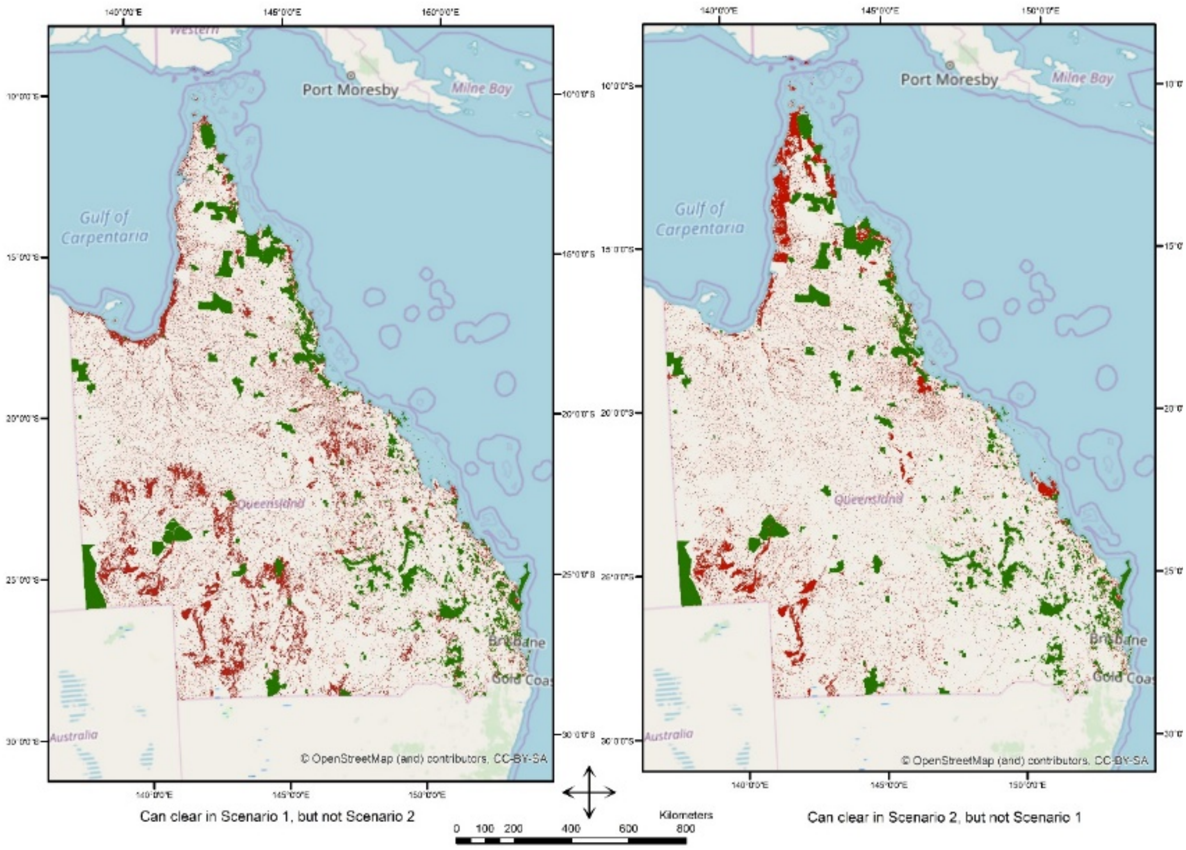


Figure A4-5 Comparison of the landscape and biophysical features in thinning clearing guidelines for each of the three scenarios. The first panel refers to the clearing guidelines in the *strict* scenario. In this panel, I describe the criteria relevant to each feature in the guideline. The middle panel shows the effect of any change from the *strict* guideline (*ie* from 2012) to the *relaxed* (*ie* from 2015). The final panel demonstrates the impact of any changes from the *relaxed* scenario to the *modern* scenario.

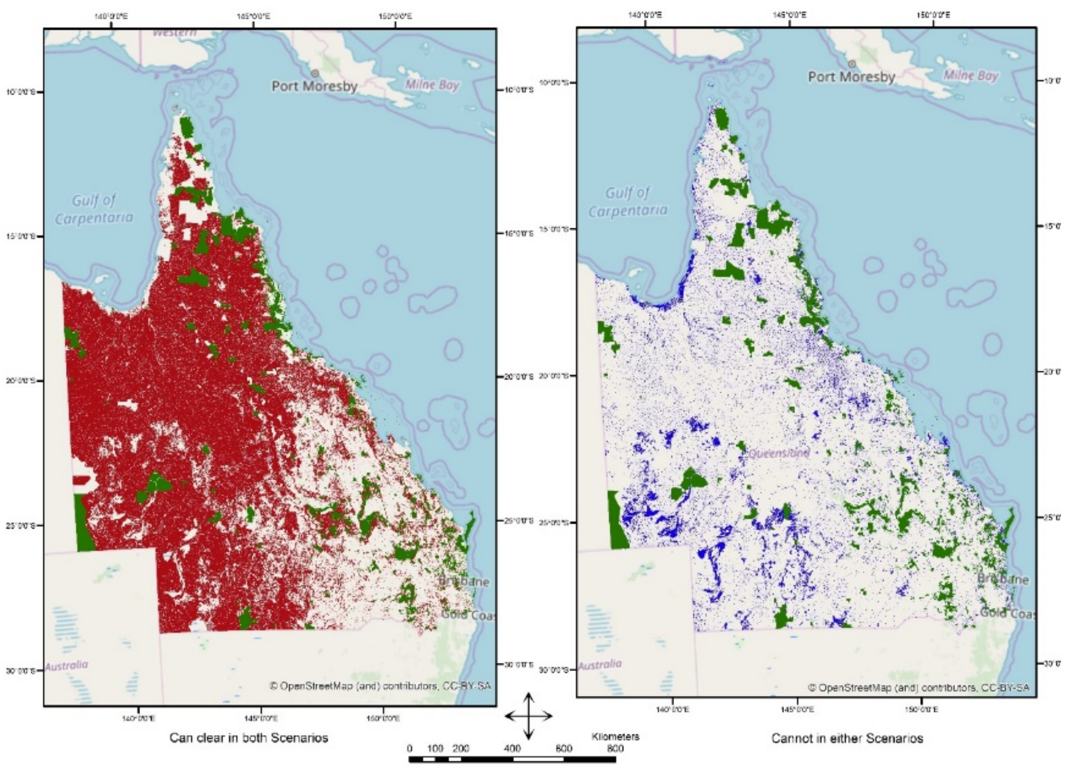
4.3 Map vegetation available for clearing

Following the above process for each clearing guideline, I produced maps of potential clearing for each clearing purpose and each scenario for both remnant vegetation (**Figures A4-1; A4-2**).

Data tables associated with each layer contain information on the extent of each polygon (or GIS shape. I summarised the total extent of remnant and high-value regrowth vegetation available for clearing by combining areas that could be cleared for any purpose into a single layer for each scenario. I subtracted the two layers create four maps: 1. potentially cleared pre-2013 but not post-2013; 2. possibly cleared post-2013 but not pre-2013; 3. possibly cleared in both scenarios, and 4. possibly cleared in neither scenario.



FigureA4-5: Distribution of non-assessable in strict but not relaxed (left) and distribution of non-assessable vegetation in relaxed but not strict (right).



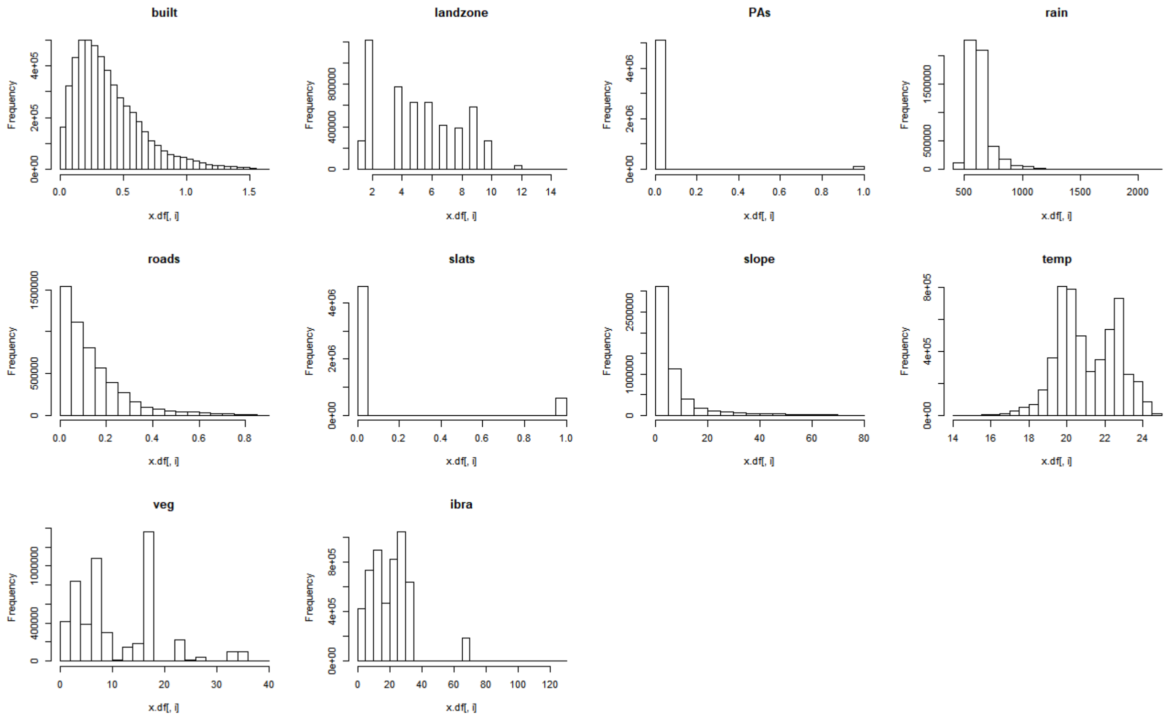
FigureA4-6: Comparisons of the distribution of vegetation which is non-assessable in both *strict* and *relaxed* scenarios (left) and the distribution of vegetation which is assessable in both scenarios (right).

Appendix 5: Exploratory Analysis and descriptive statistics for bioregions included in the study area

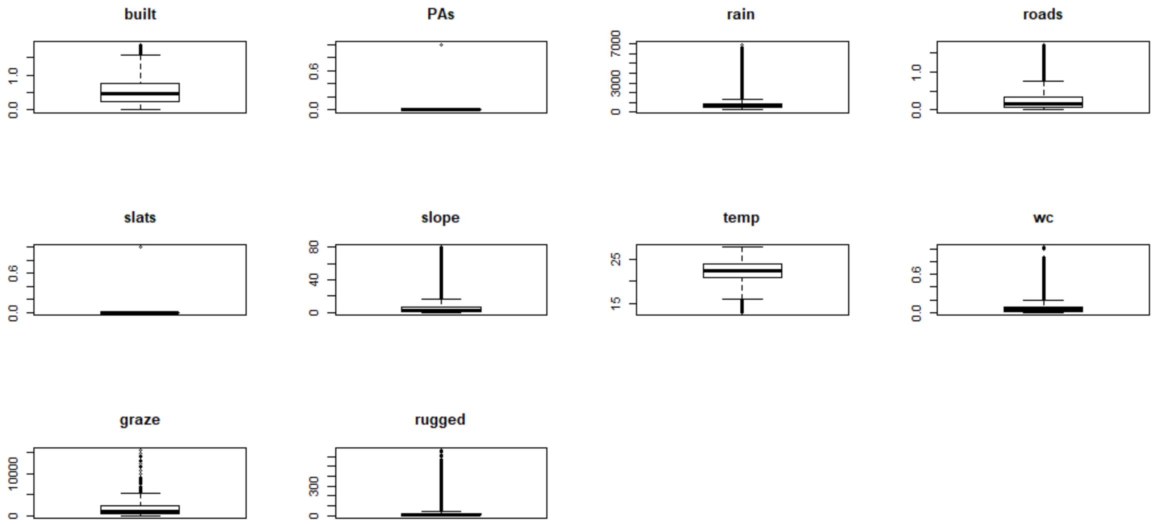
A5.1 Descriptive statistics:

In Chapter 5, I simulated probability of land clearing for nine bioregions in Queensland. In order to ensure that I have correctly specified the models used and capture the land-use variation relevant to each bioregion, I prepared some descriptive statistics of the datasets for the study region and for each bioregion. This analysis divided the study region into 15,654,832 individual pixels. Bounded to the central coordinate of each pixel was a value of each of the variables included in this analysis (co-variates). Understanding the bioregional context is a critical step in ensuring that the recommendations included here are appropriate. This section provides details on data included in this analysis, and a summary of why candidate covariates were excluded from further analysis.

For each bioregion in the study region, the distribution of co-variates were not normal. The majority of pixels in this dataset tended to be closer to built-up areas giving this data a left skew. The most common landzones are landzone 2 – coastal dunes, and landzone 4 – clay pans. There are significantly more unprotected pixels (value of "0") than protected pixels (value of "1"). The average annual rainfall across the study region is between 500-700mm per year. Similar to the distance to built-up areas variable, the distance to roads variable is left-skewed. This indicates that most of the data were closer to roads. Furthermore, according to the slats data, there were more uncleared pixels (value of "0") than cleared pixels (value of "1") in the study area. The study region was also characterised by low slopes and moderate average annual temperatures. The most common vegetation type in the study region was broad vegetation group 18 - Dry eucalypt woodlands to open woodlands primarily on sandplains or depositional plains (**Figures A5-1 & A5-2**).



FigureA5- 1:Histograms represent co-variate distribution across the State. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

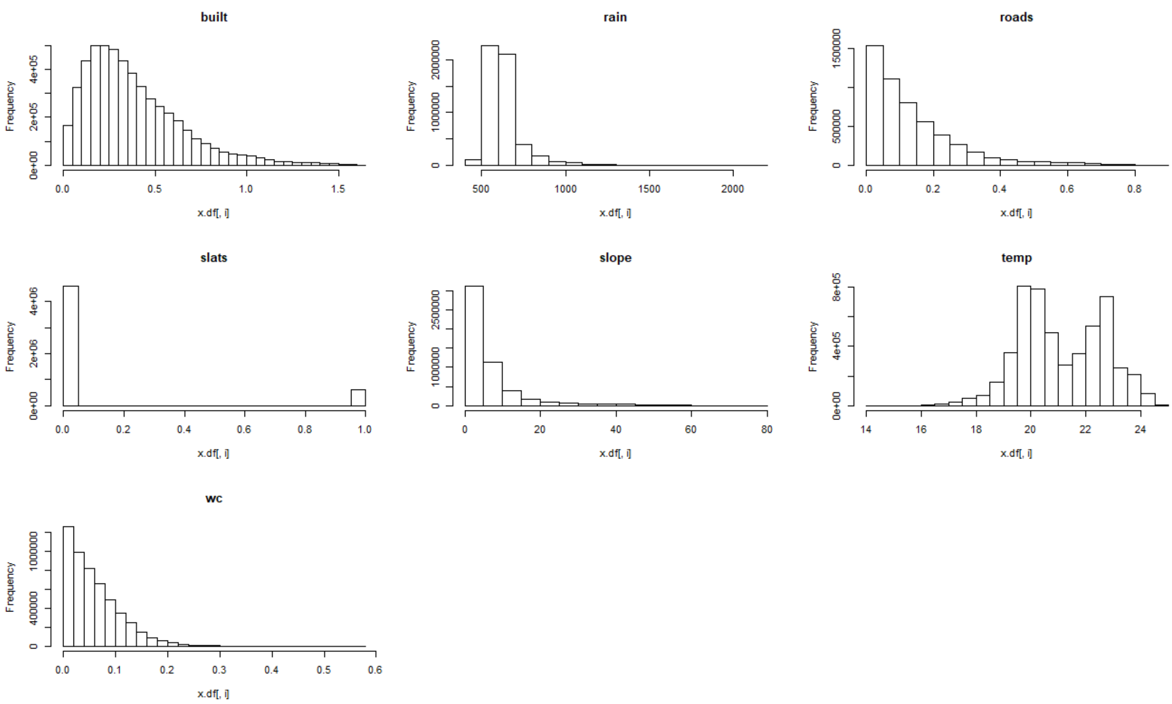


FigureA5-2: Boxplots representing co-variate distribution across the state. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent

rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

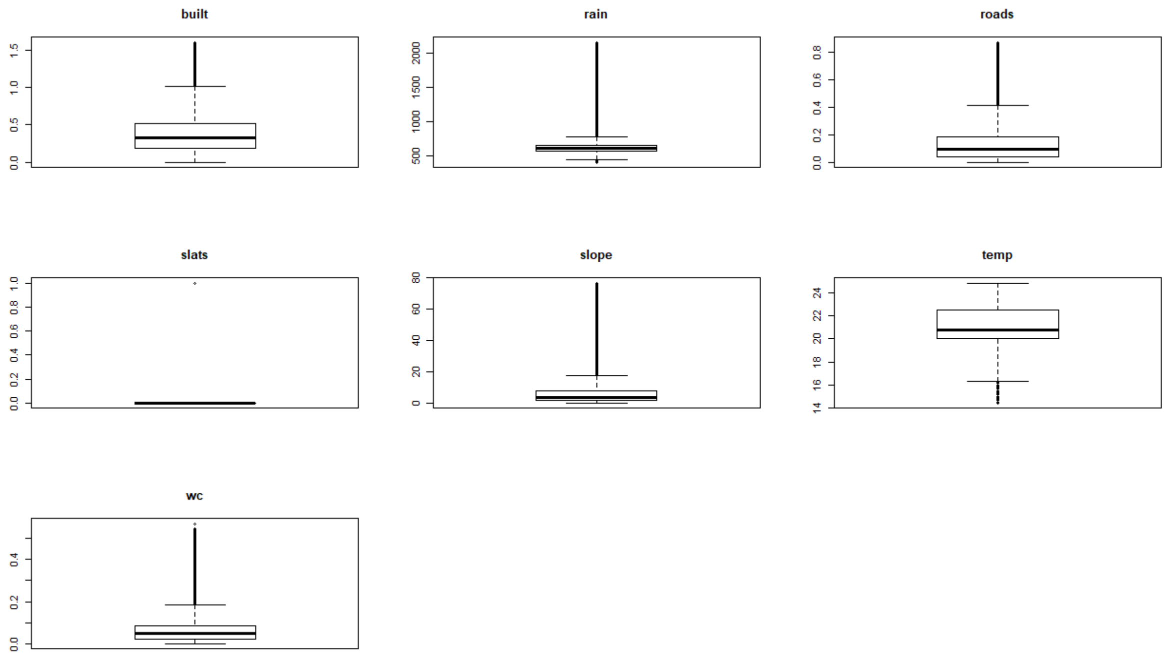
Brigalow Belt

The Brigalow Belt bioregion was divided into 5,210,930 250m*250m pixels. On average, these pixels were 0.3815 decimal degrees away from major urban areas (built) with a minimum of 0.00 dd and a maximum of 1.60dd). As was the case in the study region data, the most common landzone were landzones 2 and 4. There were 89,808 pixels in this bioregion that were classified as protected areas (having a value of “1”). The average annual rainfall in this bioregion ranged from 404mm-2165mm with a mean value of 628.1mm. Distance to roads ranged from 0.00 dd to 0.874 dd with a mean value of 0.137 dd. There were 603,946 pixels that had been cleared at least once in the past 30 years (having a value of “1”). The slope in the Brigalow Belt ranged from 0.00 per cent rise to 76.9 per cent rise and had a mean value of 6.78 per cent rise. The average annual temperature in this bioregion ranged from 14.4^{o}C to 24.90 ^{o}C and was, on average 21.15 ^{o}C. As was the case across the whole study region, the average annual temperature is bimodal – having a first peak at 19-20 ^{o}C and a second at 23.5 ^{o}C. I did not include hillshade, topographical ruggedness or grass biomass in the final model for this bioregion. For the first two, these were not significant predictors of land-clearing. For grass biomass, I noticed that in pixels where protected areas occurred, the grass biomass had been given a value of “0.” Not wanting potential false zeros to impact the model, I excluded the variable from the Brigalow Belt model.



FigureA5- 3: Histogram of each co-variate within the Brigalow Belt dataset. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm),

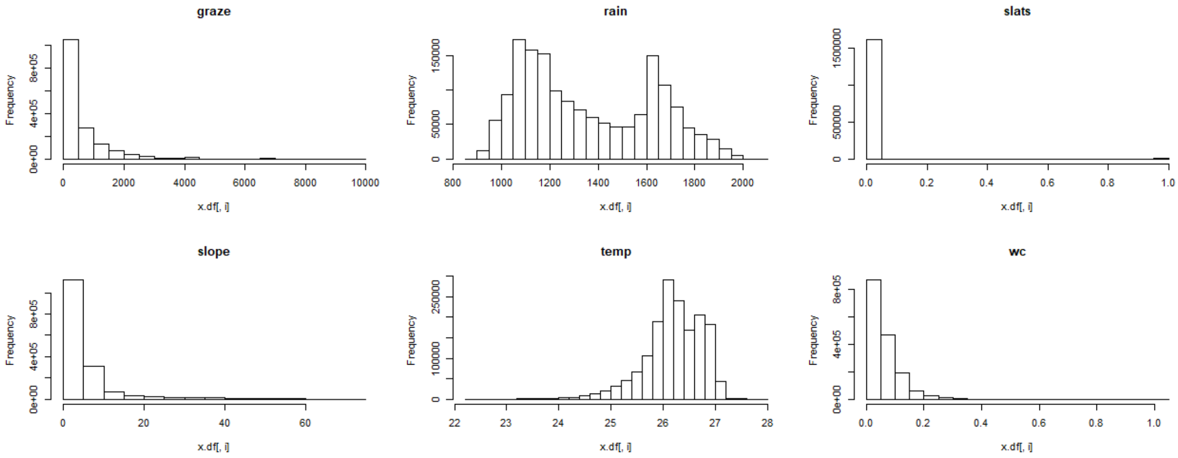
Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).



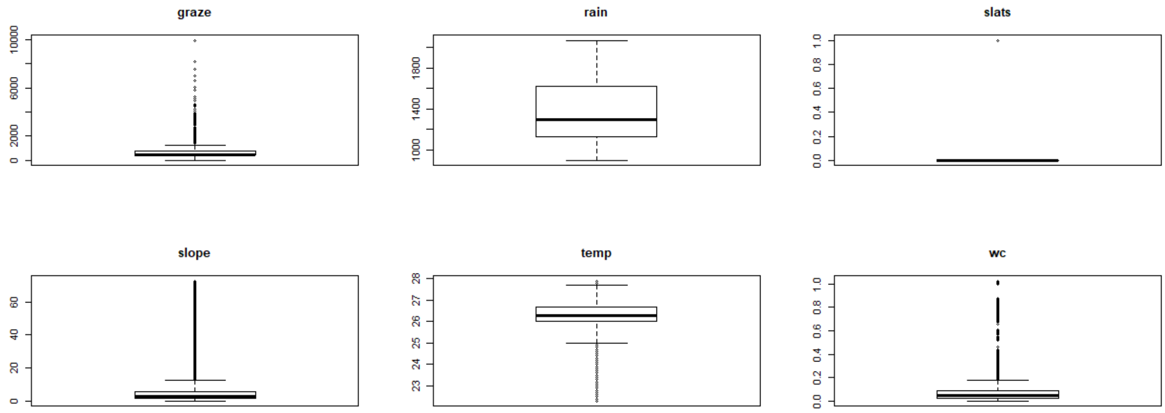
FigureA5- 4: Boxplot of bioregional data for the Brigalow Belt. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

Cape York

The Cape York bioregion was divided into 1,631,523, 250m*250m pixels. On average, these pixels had a grass biomass of 774.9 kg/ha with a minimum of 0.00 kg/ha and a maximum of 9,951.0 kg/ha. There were 190,750 pixels in this bioregion that were classified as protected areas (having a value of “1”). The average annual rainfall in this bioregion ranged from 898 to 2,069 mm per year with a mean value of 1,360 mm per year. There were 5,557 pixels that had been cleared at least once in the past 30 years (having a value of “1”). The slope in the Cape York bioregion ranged from 0.00 per cent rise to 72.7 per cent rise and had a mean value of 5.67 per cent rise. The average annual temperature in this bioregion ranged from 22.30^{o}C to 27.90 ^{o}C and was, on average, 26.24 ^{o}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 1.025, with an average distance of 0.061 decimal degrees. I did not include the following non-significant predictors in the final model for Cape York: distance to built-up areas, distance to roads, hillshade, or topographical ruggedness.



FigureA5-5: Histogram of each co-variate within the Cape York dataset. Boxplot of bioregional data for the Brigalow Belt. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

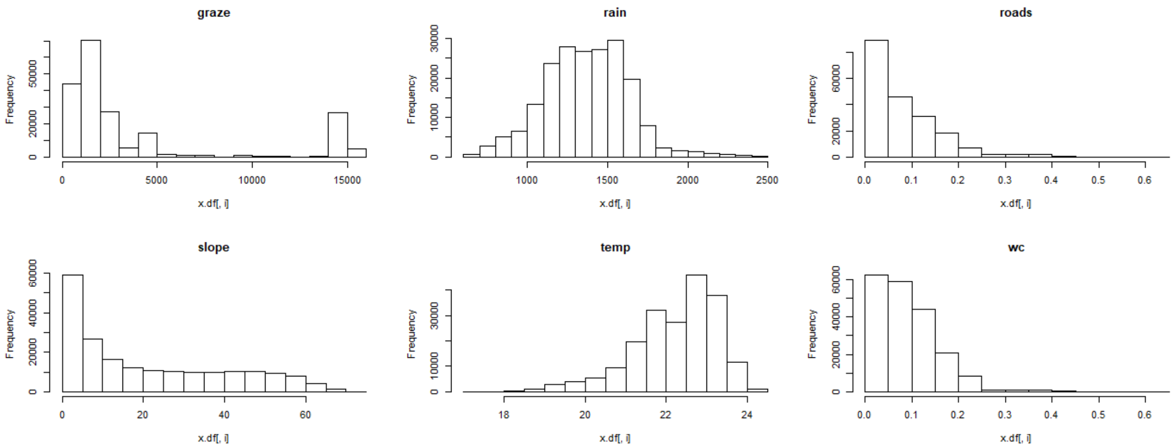


FigureA5- 6: Boxplot of bioregional data for the Cape York dataset. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

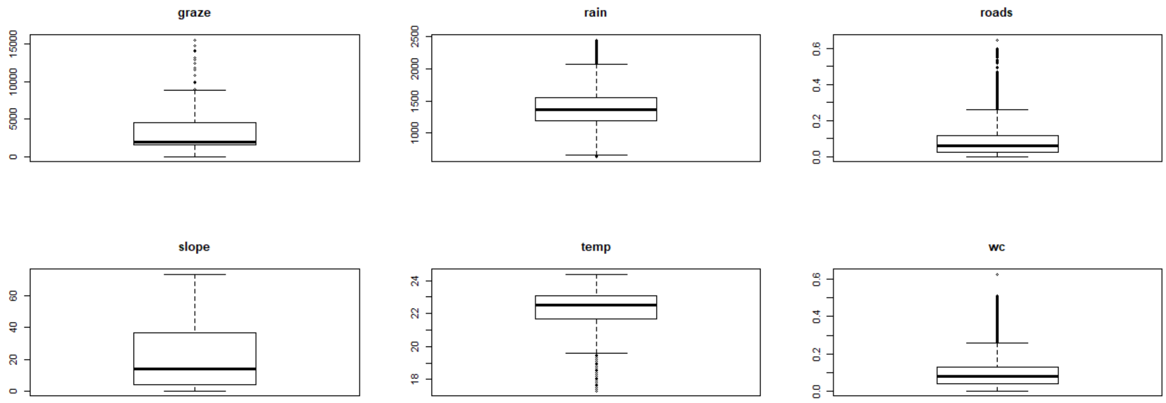
Central Queensland Coast

The Central Queensland Coast bioregion was divided into 198,695 250m*250m pixels. On average, these pixels had a grass biomass of 4,112 kg/ha with a minimum of 0.00 kg/ha and a maximum of 15,607 kg/ha. There were 8,337 pixels in this bioregion that were classified as protected areas (having a value of “1”). The average annual rainfall in this bioregion ranged from

635 to 2,448 mm per year with a mean value of 1,371 mm per year. Distance to roads ranged from 0.00 dd to 0.648 dd with a mean value of 0.081 dd. There were 7,334 pixels that had been cleared at least once in the past 30 years (having a value of "1"). The slope in the Central Queensland Coast bioregion ranged from 0.00 per cent rise to 73.86 per cent rise and had a mean value of 21.00 per cent rise. The average annual temperature in this bioregion ranged from 17.30ºC to 24.40 ºC and was, on average 22.28 ºC. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.629 with an average distance of 0.090 decimal degrees. I did not include the following non-significant predictors in the final model for Central Queensland Coast: distance to built-up areas, hillshade, or topographical ruggedness.



FigureA5-7: Histogram of each co-variate within the Central Queensland Coast dataset. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

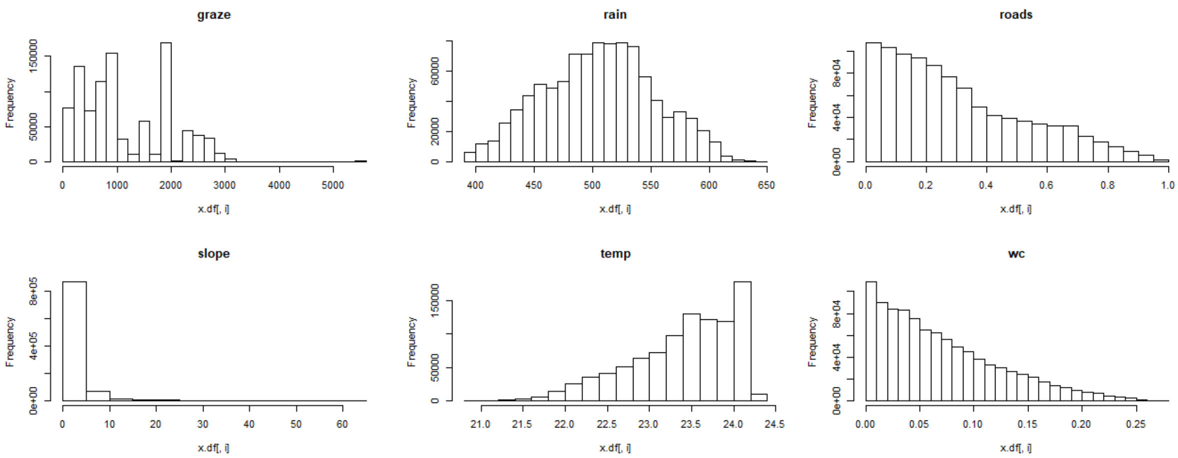


FigureA5-8: Boxplot of bioregional data for the Central Queensland Coast. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm),

Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

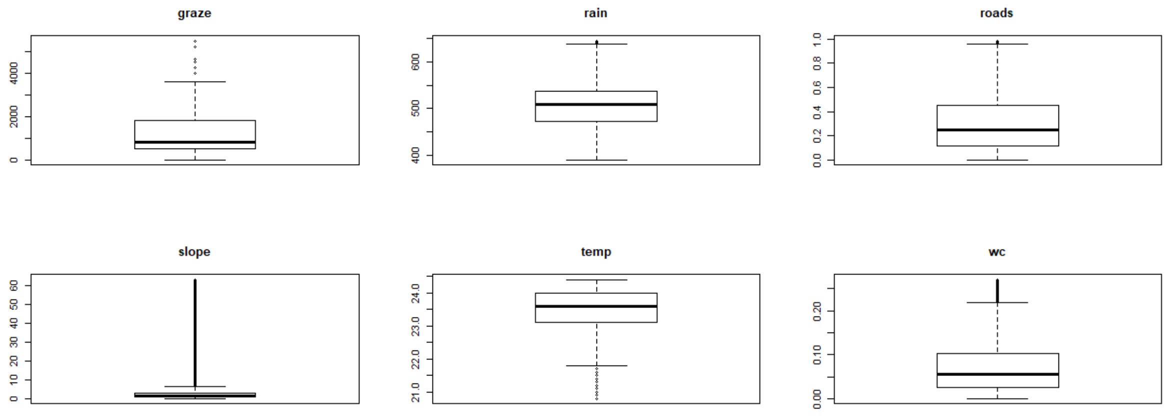
Desert Uplands

The Desert Uplands bioregion was divided into 970,348 250m*250m pixels. There were 88,368 pixels that had been cleared at least once in the past 30 years (having a value of "1"). There were 23,829 pixels in this bioregion that were classified as protected areas (having a value of "1"). On average, these pixels had a grass biomass of 1,150 kg/ha with a minimum of 0.00 kg/ha and a maximum of 5,494 kg/ha. The average annual rainfall in this bioregion ranged from 390 to 645 mm per year with a mean value of 506 mm per year. Distance to roads ranged from 0.00 to 0.987 dd with a mean value of 0.302 dd. The slope in the Desert Uplands bioregion ranged from 0.00 per cent rise to 63.04 per cent rise and had a mean value of 2.47 per cent rise. The average annual temperature in this bioregion ranged from 20.80^{o}C to 24.40 ^{o}C and was, on average 23.45 ^{o}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.271 with an average distance of 0.069 decimal degrees. I did not include the following non-significant predictors in the final model for Desert Uplands: distance to built-up areas, hillshade, or topographical ruggedness.



FigureA5-9: Histogram of bioregional data for the Desert Uplands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and

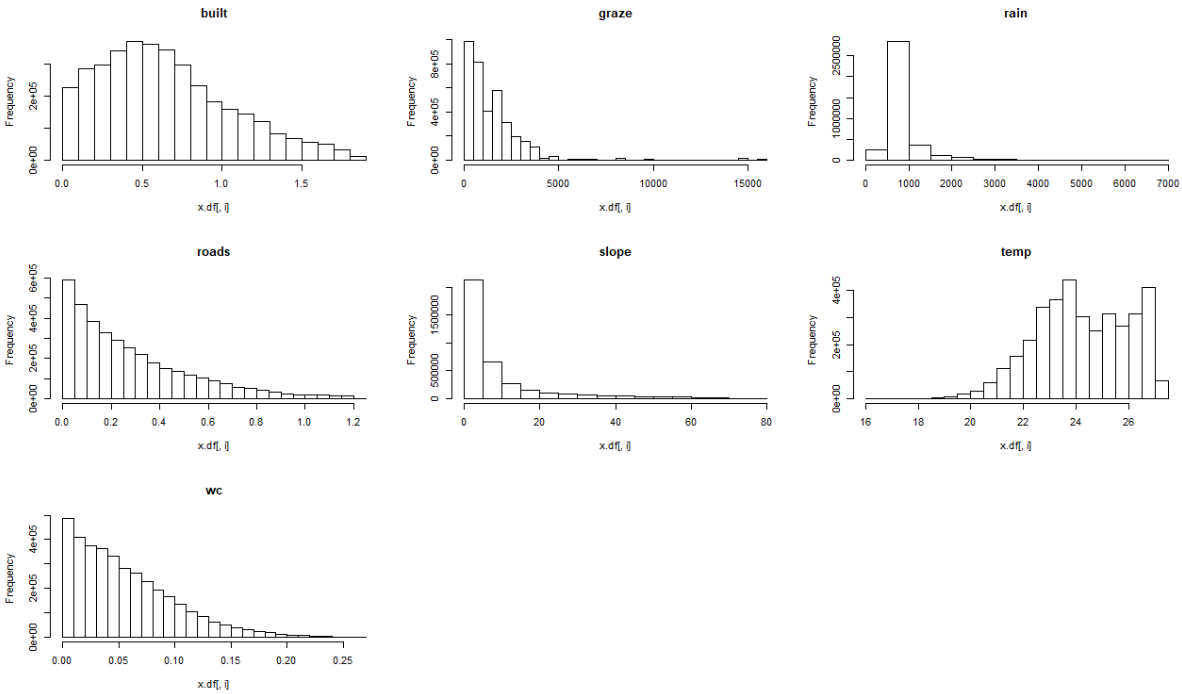
temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).



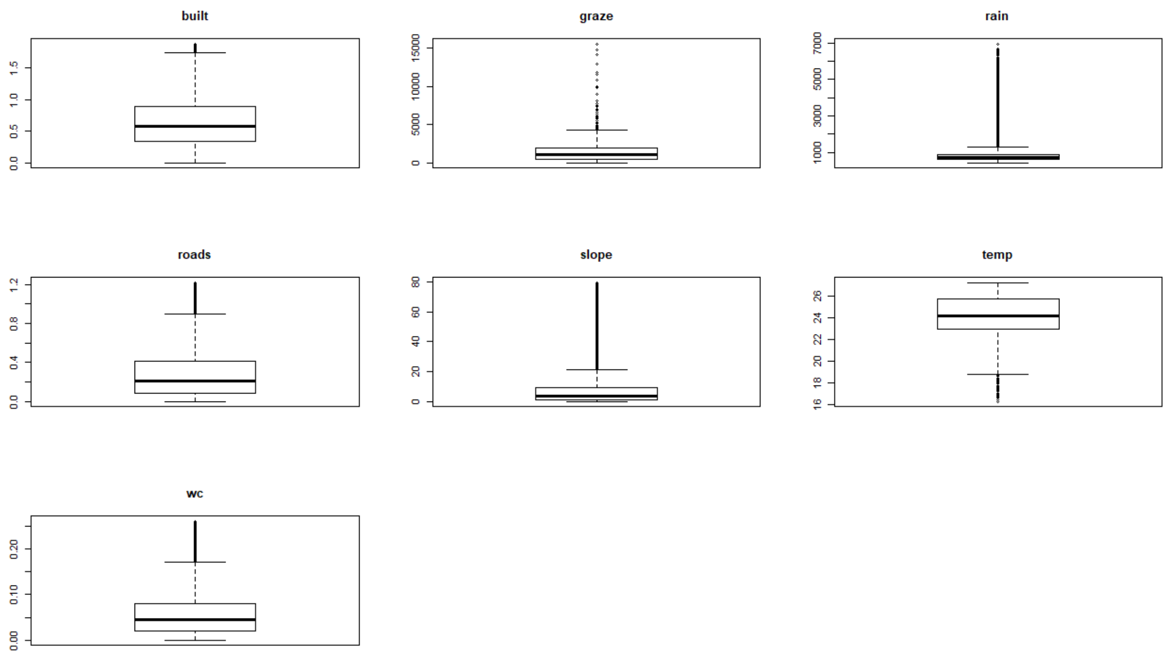
FigureA5-10: Boxplot of bioregional data for the Desert Uplands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

Einasleigh Uplands

The Einasleigh Uplands bioregion was divided into 3,663,854 250m*250m pixels. There were 37,235 pixels that had been cleared at least once in the past 30 years (having a value of “1”). There were 176,367 pixels in this bioregion that were classified as protected areas (having a value of “1”). The distance to built-up areas in this bioregion ranged from 0.00 to 1.88 decimal degrees with an average value of 0.645 decimal degrees. On average, these pixels had a grass biomass of 1,457 kg/ha with a minimum of 0.00 kg/ha and a maximum of 15,607 kg/ha. The average annual rainfall in this bioregion ranged from 414 to 6,954 mm per year with a mean value of 833 mm per year. Distance to roads ranged from 0.00 to 1.22 dd with a mean value of 0.280 dd. The slope in the Einasleigh Uplands bioregion ranged from 0.00 per cent rise to 79.52 per cent rise and had a mean value of 8.43 per cent rise. The average annual temperature in this bioregion ranged from 16.3^{O}C to 27.3 ^{O}C and was, on average 24.3 ^{O}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.261 with an average distance of 0.055 decimal degrees. I did not include the following non-significant predictors in the final model for Einasleigh Uplands: distance to built-up areas, hillshade, or topographical ruggedness.



FigureA5-11: Histogram of bioregional data for the Einasleigh Uplands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

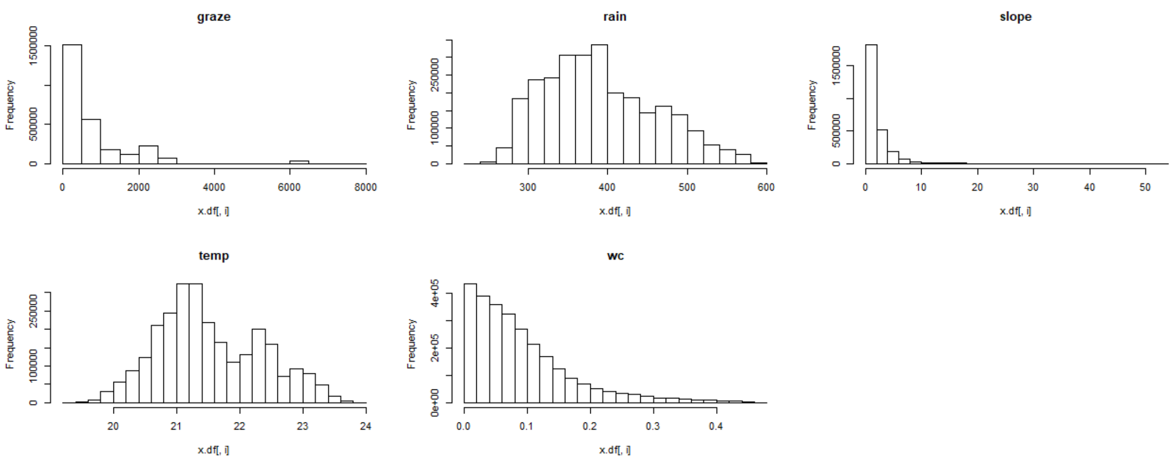


FigureA5-12: Boxplot of bioregional data for the Einasleigh Uplands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and

temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

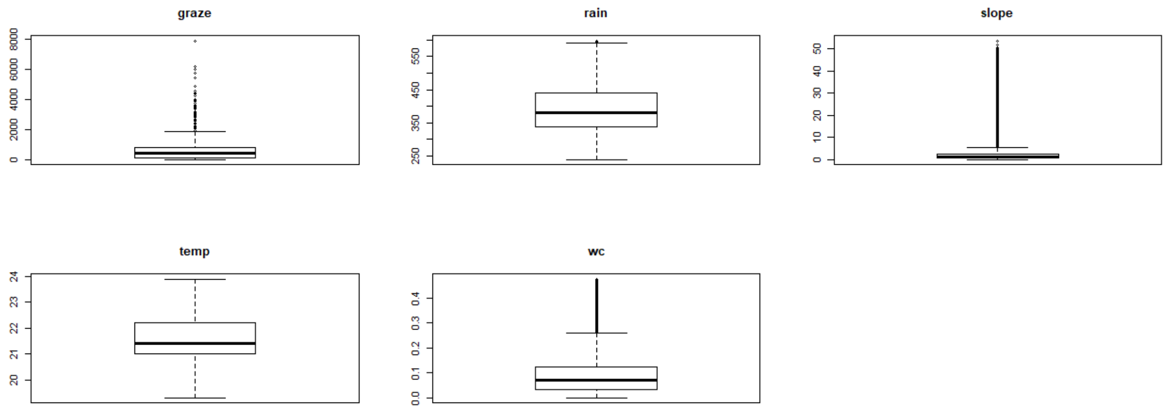
Mugla Lands

The Mulga Lands bioregion was divided into 2,707,334 250m*250m pixels. There were 73,976 pixels that had been cleared at least once in the past 30 years (having a value of “1”). There were 263,017 pixels in this bioregion that were classified as protected areas (having a value of “1”). On average, these pixels had a grass biomass of 749 kg/ha with a minimum of 8 kg/ha and a maximum of 7,902 kg/ha. The average annual rainfall in this bioregion ranged from 239 to 598 mm per year with a mean value of 391 mm per year. The slope in the Mulga Lands bioregion ranged from 0.00 per cent rise to 53.67 per cent rise and had a mean value of 2.14 per cent rise. The average annual temperature in this bioregion ranged from 19.3^{O}C to 23.9 ^{O}C and was, on average 21.6 ^{O}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.476 with an average distance of 0.090 decimal degrees. I did not include the following non-significant predictors in the final model for Mulga Uplands: distance to built-up areas, distance to roads, hillshade, or topographical ruggedness.



FigureA5-13: Histogram of bioregional data for the Mulga Lands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and

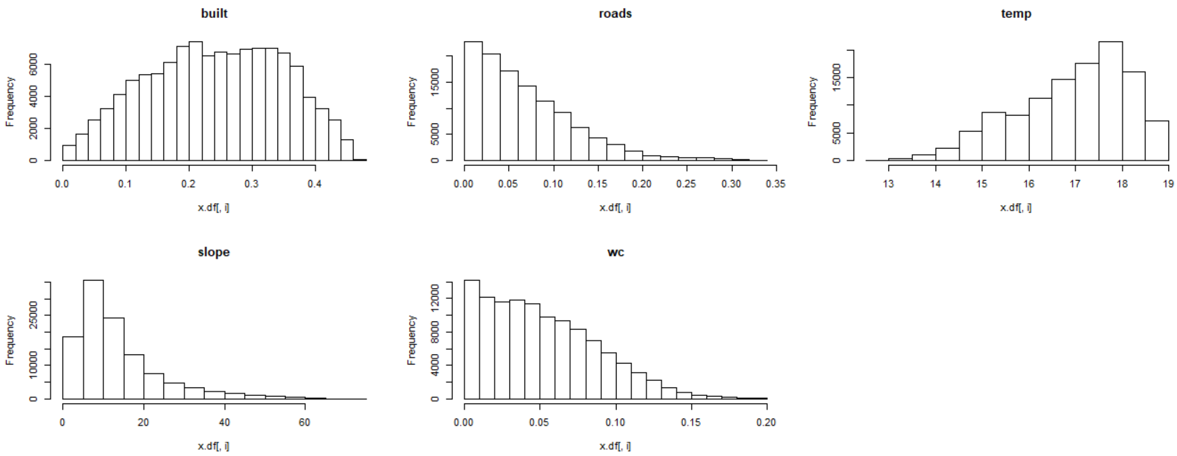
temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).



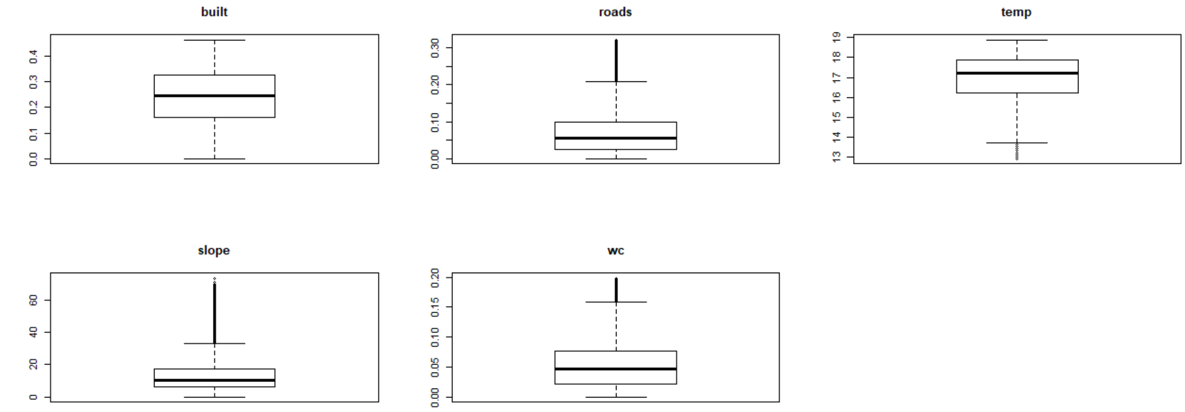
FigureA5-14: Boxplot of bioregional data for the Mulga Lands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

New England Tablelands

The New England Tablelands bioregion was divided into 113,636 250m*250m pixels. There were 8,122 pixels that had been cleared at least once in the past 30 years (having a value of "1"). There were 2,241 pixels in this bioregion that were classified as protected areas (having a value of "1"). On average, these pixels were 0.244 decimal degrees away from built-up areas with a minimum of 0.00 decimal degrees and a maximum of 0.464 decimal degrees. The distance to roads was 0.068 decimal degrees in this bioregion and ranged from 0.00 to 0.322 decimal degrees. The slope in the New England Tablelands bioregion ranged from 0.00 per cent rise to 73.36 per cent rise and had a mean value of 13.45 per cent rise. The average annual temperature in this bioregion ranged from 12.9^{o}C to 18.9 ^{o}C and was, on average 17.0 ^{o}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.198 with an average distance of 0.052 decimal degrees. I did not include the following non-significant predictors in the final model for the New England Tablelands: grass biomass, average annual rainfall, hillshade, or topographical ruggedness.



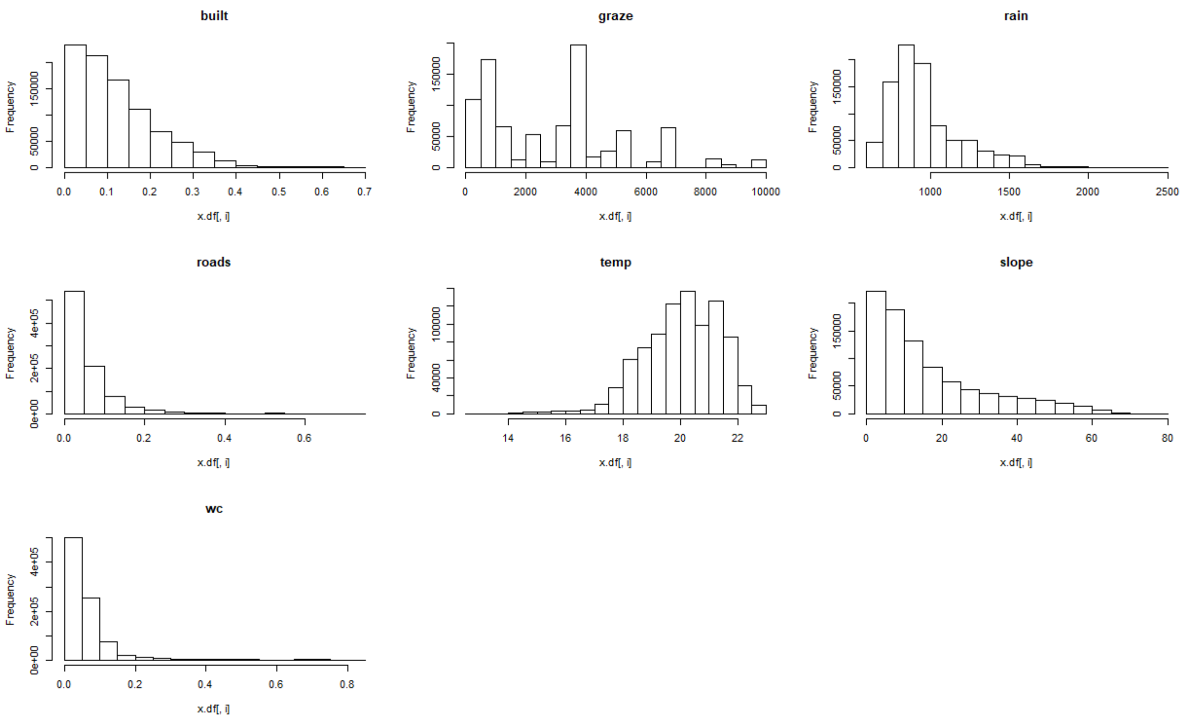
FigureA5-15: Histogram of bioregional data for the New England Tablelands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).



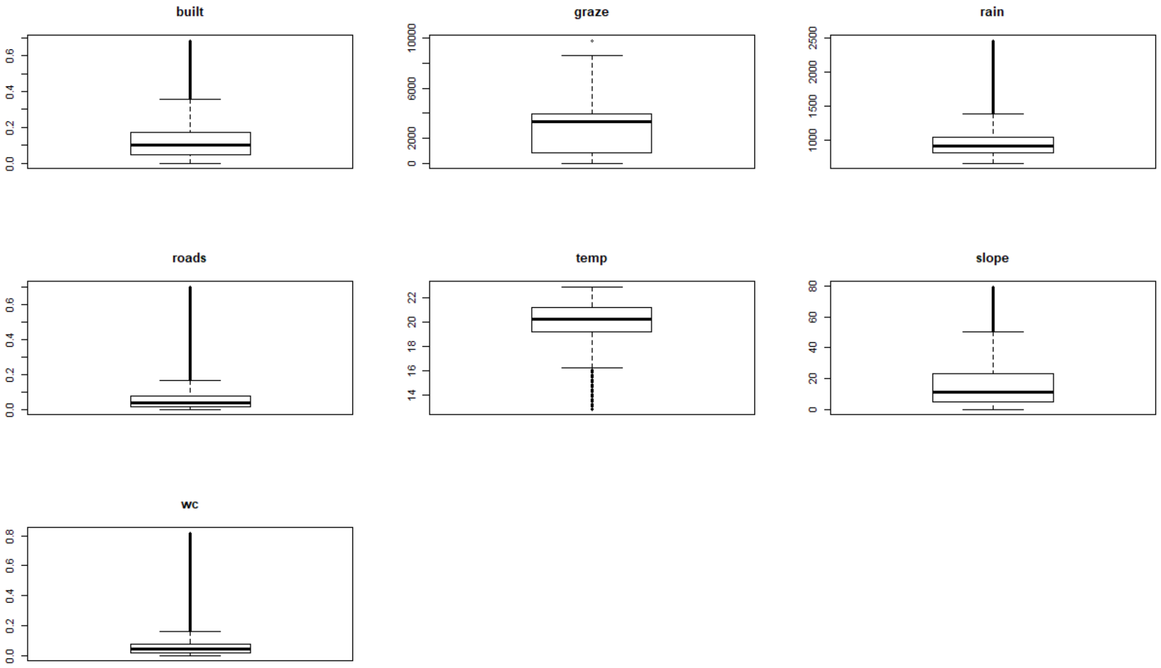
FigureA5- 16 Boxplot of bioregional data for the New England Tablelands. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

Southeast Queensland

The Southeast Queensland bioregion was divided into 890,454 250m*250m pixels. There were 8,122 pixels that had been cleared at least once in the past 30 years (having a value of "1"). There were 2,241 pixels in this bioregion that were classified as protected areas (having a value of "1"). On average, these pixels were 0.120 decimal degrees away from built-up areas with a minimum of 0.00 decimal degrees and a maximum of 0.684 decimal degrees. On average, these pixels had a grass biomass of 2,990 kg/ha with a minimum of 0 kg/ha and a maximum of 9,842 kg/ha. The mean distance to roads was 0.0568 decimal degrees in this bioregion and ranged from 0.00 to 0.701 decimal degrees. The distance to rainfall per year was 960mm and ranged from 654 to 2,469 mm. The slope in the Southeast Queensland bioregion ranged from 0.00 per cent rise to 79.6 per cent rise and had a mean value of 16.4 per cent rise. The average annual temperature in this bioregion ranged from 12.8^{O}C to 22.9 ^{O}C and was, on average 20.1 ^{O}C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.82 with an average distance of 0.063 decimal degrees. I did not include the following non-significant predictors in the final model for Southeast Queensland: hillshade, or topographical ruggedness.



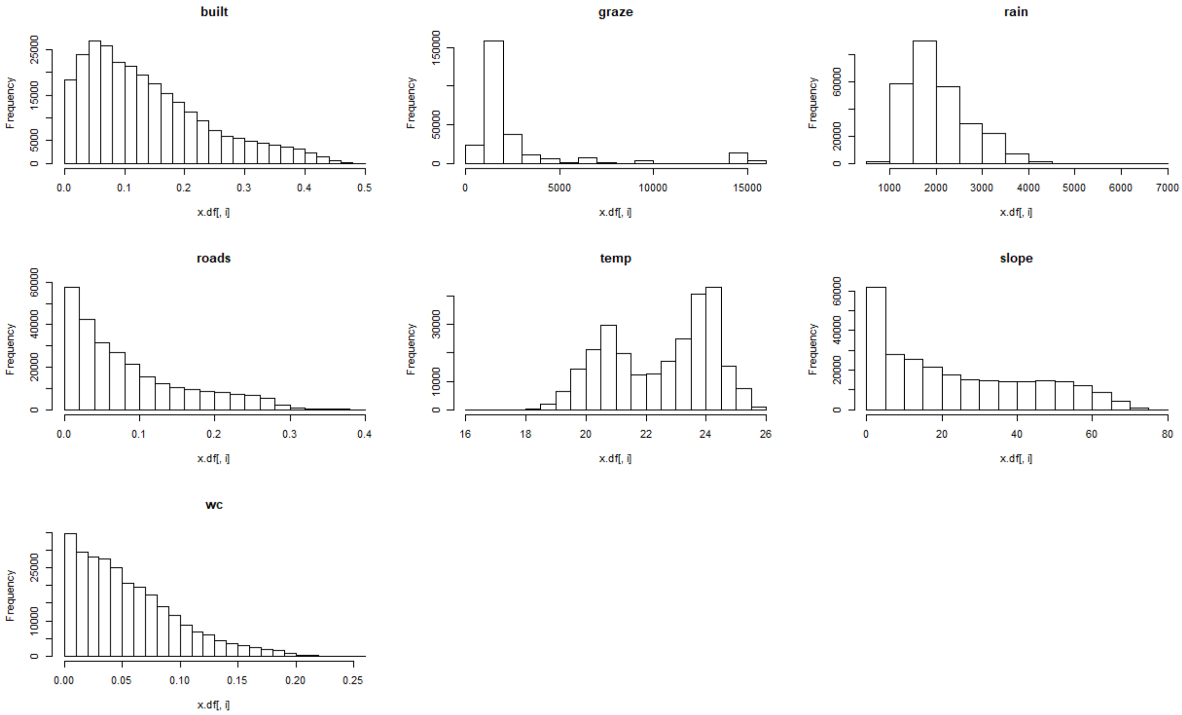
FigureA5-17: Histogram of bioregional data for the Southeast Queensland. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).



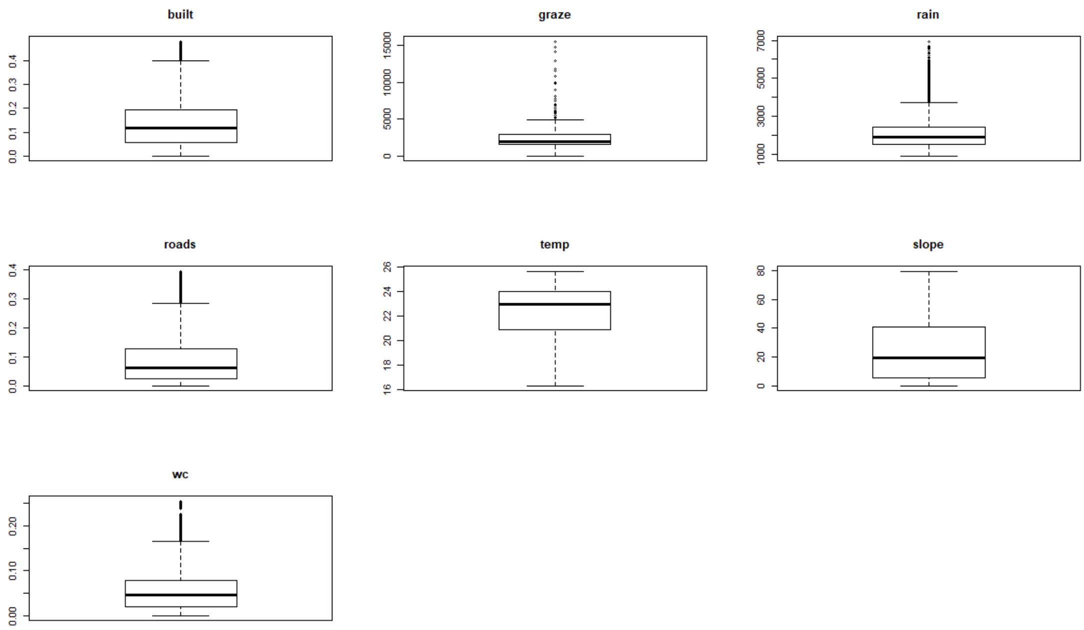
FigureA5-18: Boxplot of bioregional data for the Southeast Queensland. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

Wet Tropics

The Wet Tropics bioregion was divided into 268,058 250m*250m pixels. There were 6,004 pixels that had been cleared at least once in the past 30 years (having a value of "1"). There were 118,296 pixels in this bioregion that were classified as protected areas (having a value of "1"). On average, these pixels were 0.138 decimal degrees away from built-up areas with a minimum of 0.00 decimal degrees and a maximum of 0.480 decimal degrees. On average, these pixels had a grass biomass of 3,076 kg/ha with a minimum of 0 kg/ha and a maximum of 15,607 kg/ha. The mean distance to roads was 0.086 decimal degrees in this bioregion and ranged from 0.00 to 0.396 decimal degrees. The distance to rainfall per year was 2,046 mm and ranged from 902 to 6,954 mm. The slope in the Wet Tropics bioregion ranged from 0.00 per cent rise to 79.5 per cent rise and had a mean value of 24.2 per cent rise. The average annual temperature in this bioregion ranged from 16.3 °C to 25.7 °C and was, on average 22.6 °C. In this bioregion, the distance from major watercourses ranged from 0.00 to 0.26 with an average distance of 0.055 decimal degrees. I did not include the following non-significant predictors in the final model for Wet Tropics: hillshade, or topographical ruggedness.



FigureA5-19: Histogram of bioregional data for the Wet Tropics. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads = Distance to state-controlled roads (decimal degrees), slope = Slope (percent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

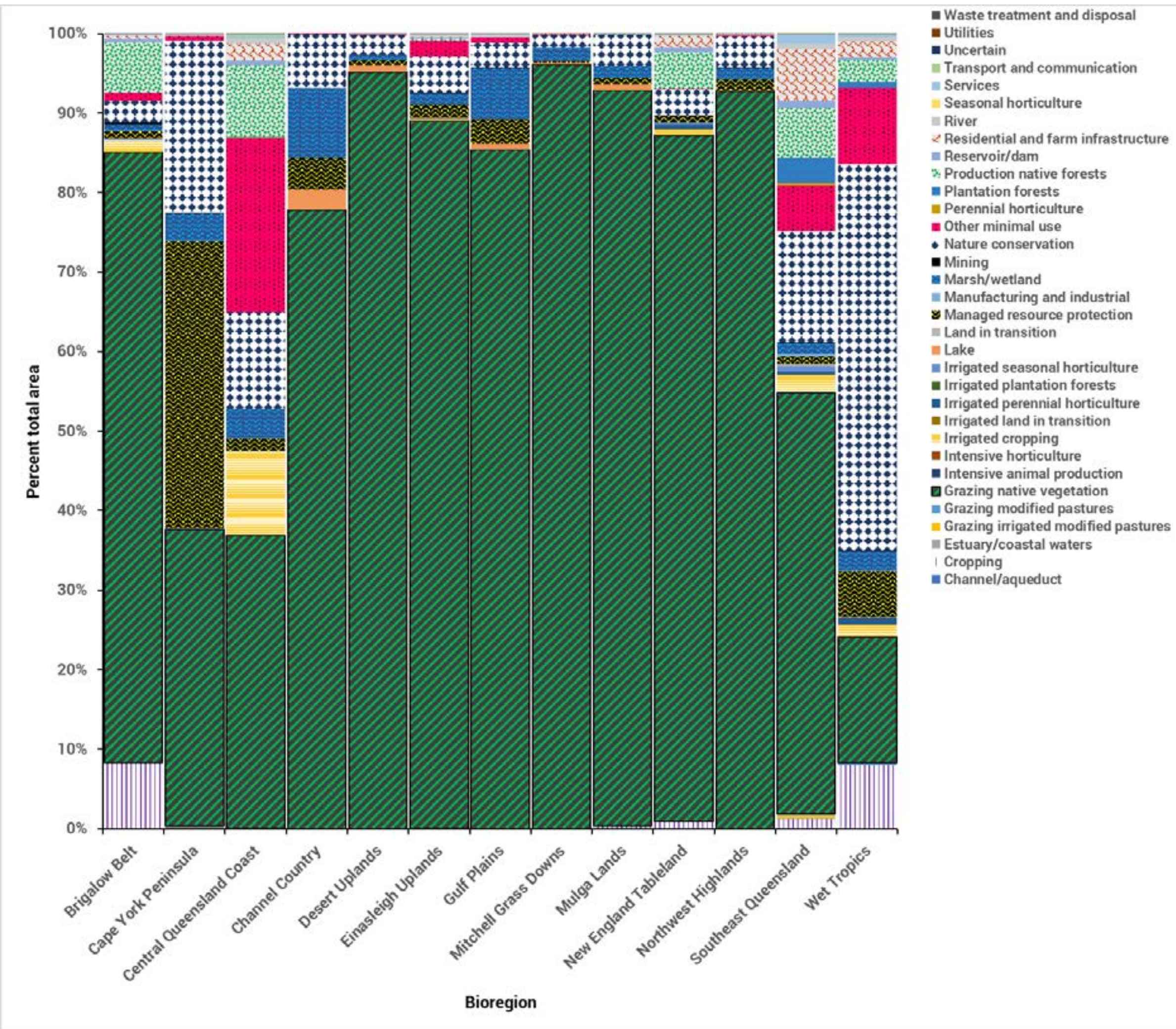


FigureA5- 20 Boxplot of bioregional data for the Southeast Queensland. Built = Distance to Built-up areas (decimal degrees), graze = grass biomass (kg/ha), rain = Rainfall (mm), Roads =

Distance to state-controlled roads (decimal degrees), slope = Slope (per cent rise), and temp = average annual temperature (OC), wc = Distance to major watercourses(decimal degrees).

A5.2 Dominant land uses in Queensland's bioregions

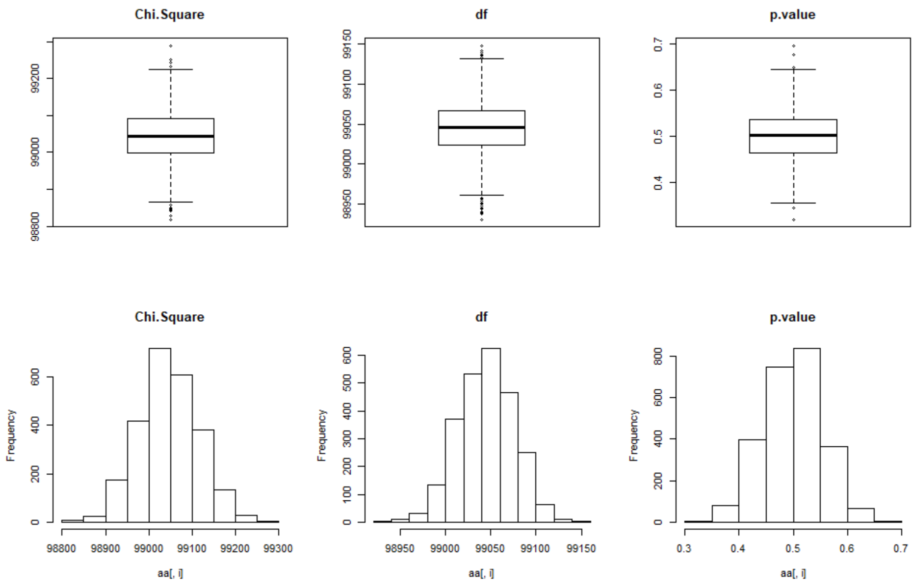
Regional variation in land-use plays a significant role in understanding the contextual drivers of land clearing. The probability of land clearing is various according to bioregion, and, this could be due to variations in the dominant land-use. I investigated the dominant land-use by summarising data from the Queensland Governments Land-use Mapping Program (QLUMP) (Queensland Government. 2018). This spatial dataset categorises the dominant land use of polygons (or spatial shapes) across Queensland. In ArcGIS (Esri 2006) v10.7.1, I summarised total area of secondary land-uses for each of Queensland's 13 bioregions. The dominant land-use for 12 of the 13 bioregions was grazing on native vegetation. The only bioregion where this wasn't the case was the Wet Tropics. In this bioregion, the dominant land-use was nature conservation (967024 ha, 49%). In general, the smallest land-uses tended to be utilities and waste water treatment facilities (between 35 and 2500 ha) as well as channels and aqueducts between 1 and 4846 ha). The Brigalow Belt bioregion is dominated by native pasture grazing (77%) and cropping (8%). The Cape York Peninsula's area was dominated by both grazing and natural resource management with over 4.4 million hectares (36%) allocated for natural resource production. Central Queensland Coast bioregion is dominated by native pasture grazing (37%) and irrigated cropping (10%) and other minimal use production (22%). The Desert Uplands, Einasleigh Uplands, Mitchell Grass Downs, Mulga Lands and Northwest Highlands bioregions are predominately native pasture production (95%, 89%, 96%, 93% and 93%). The Southeast Queensland bioregion is dominated by native pasture production (53%), nature conservation (14%) and residential areas (7%). The variation land-use has implications for deforestation and management in each bioregion.



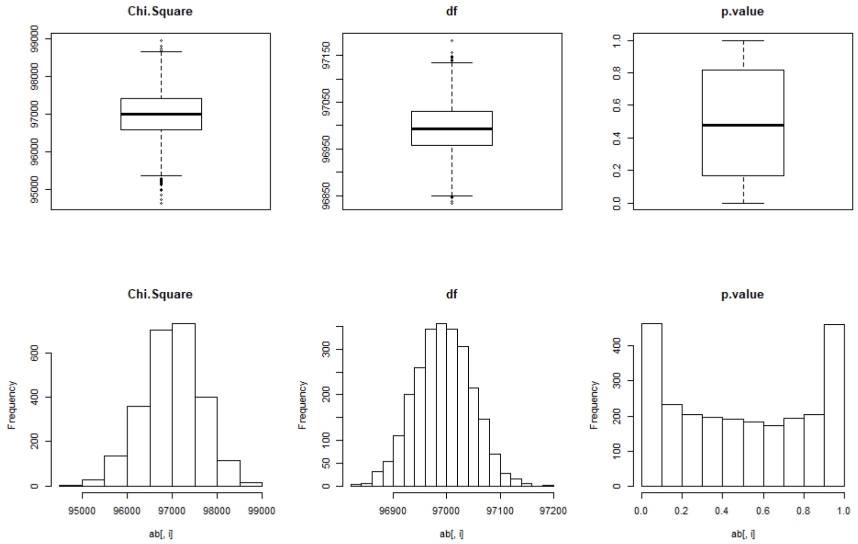
FigureA5-21: The secondary land-use per bioregion represented as a proportion of the total area of each bioregion. The data presented here was obtained from the Queensland Government's Land use Mapping Program (QLULMP) (Queensland Government. 2018). Area summaries were calculated in ArcMap 10.7 (Esri 2006).

A5.3 Tests for model fit – simulations of Pearson's Chi-squared

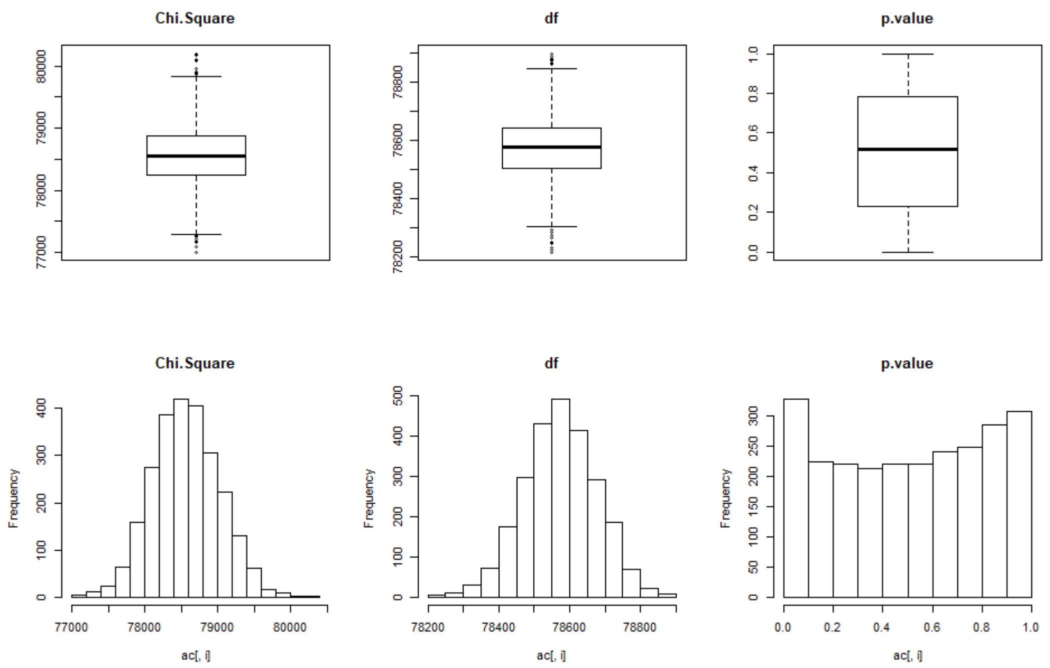
I obtained Chi-squared values by taking 2,500 random samples of 100,000 rows of data within each bioregion and comparing the predicted values with the values observed by the data. Using this robust approach, I was able to safely accept the null hypothesis: there is no significant difference between the predicted and observed value ($p>0.05$) for all bioregions. I found that the Chi-squared test statistic, degrees of freedom and p.values were all normally distributed in each bioregion (**Figures A5-22 to A5-30**).



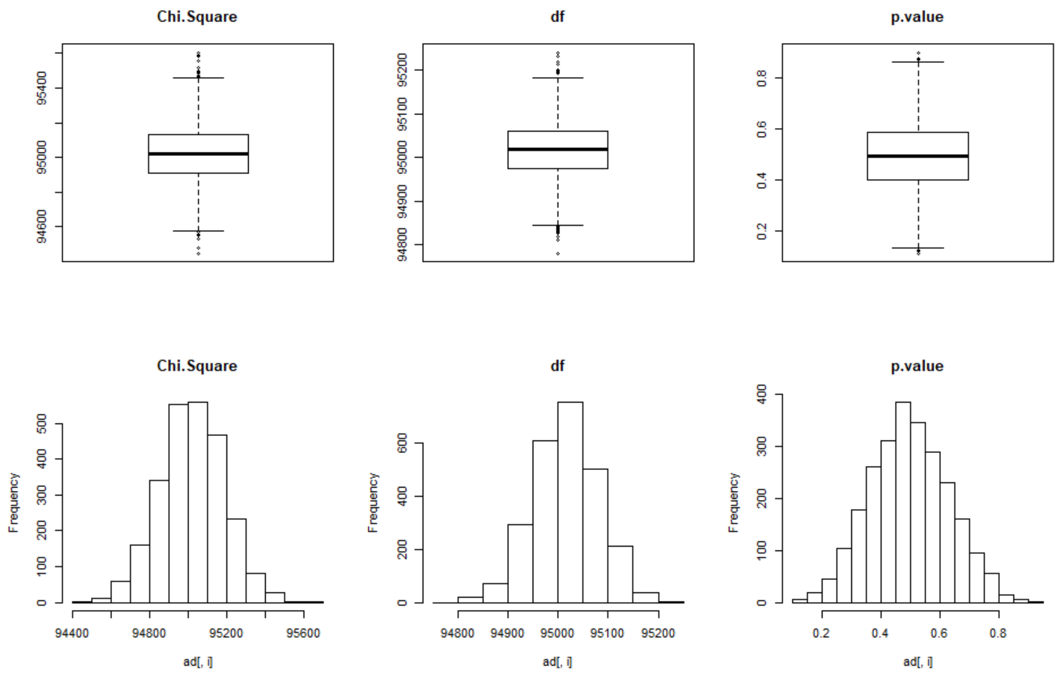
FigureA5-22: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Brigalow Belt Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



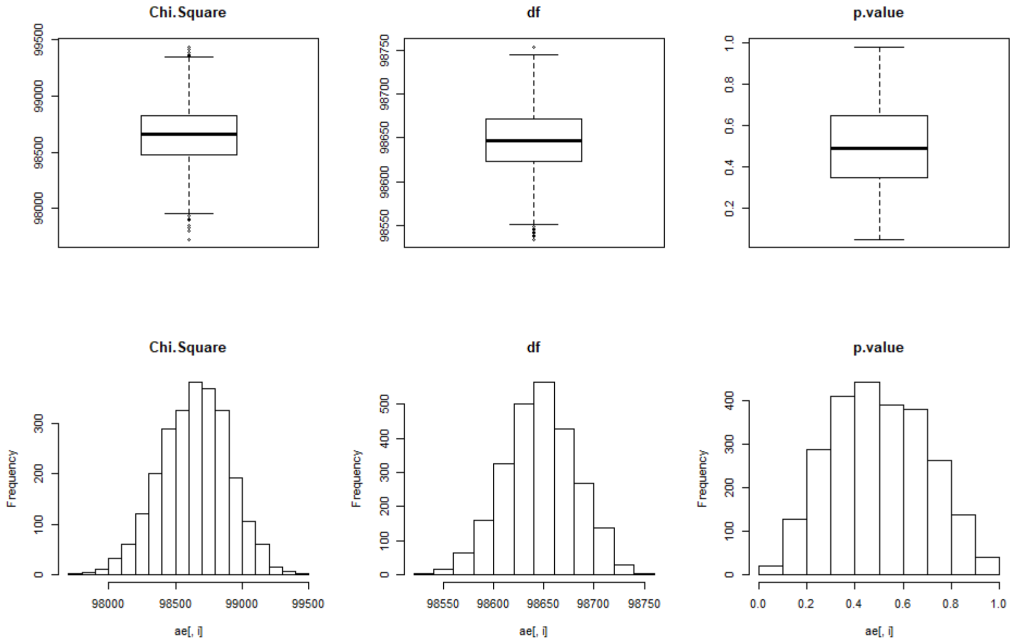
FigureA5-23: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Cape York. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



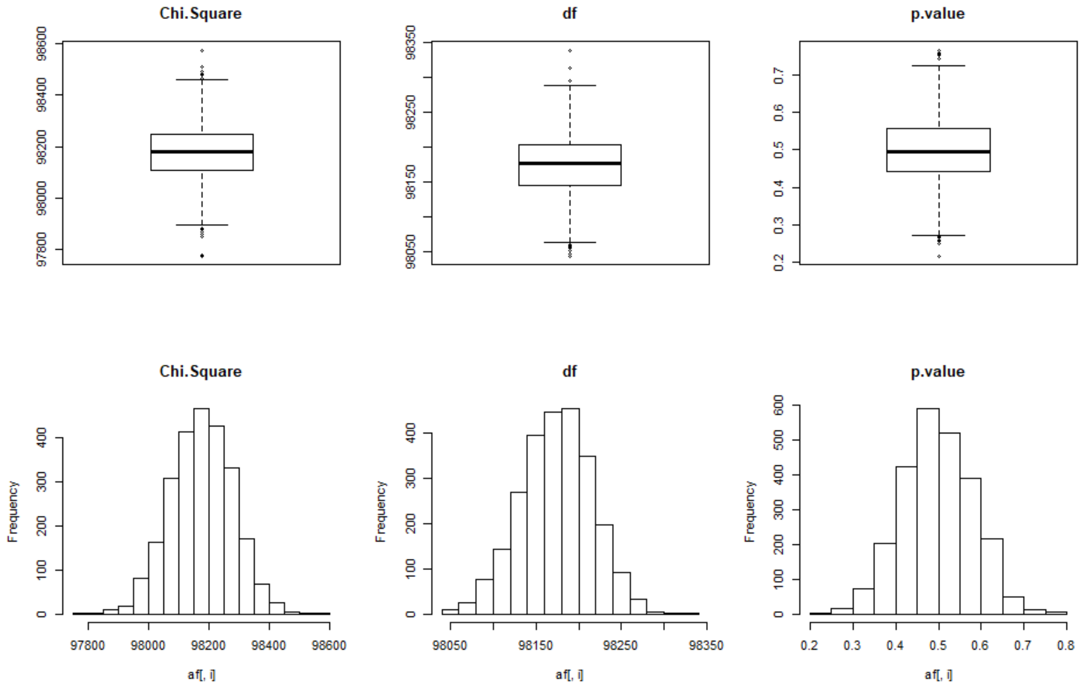
FigureA5-24: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Central Queensland Coast Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



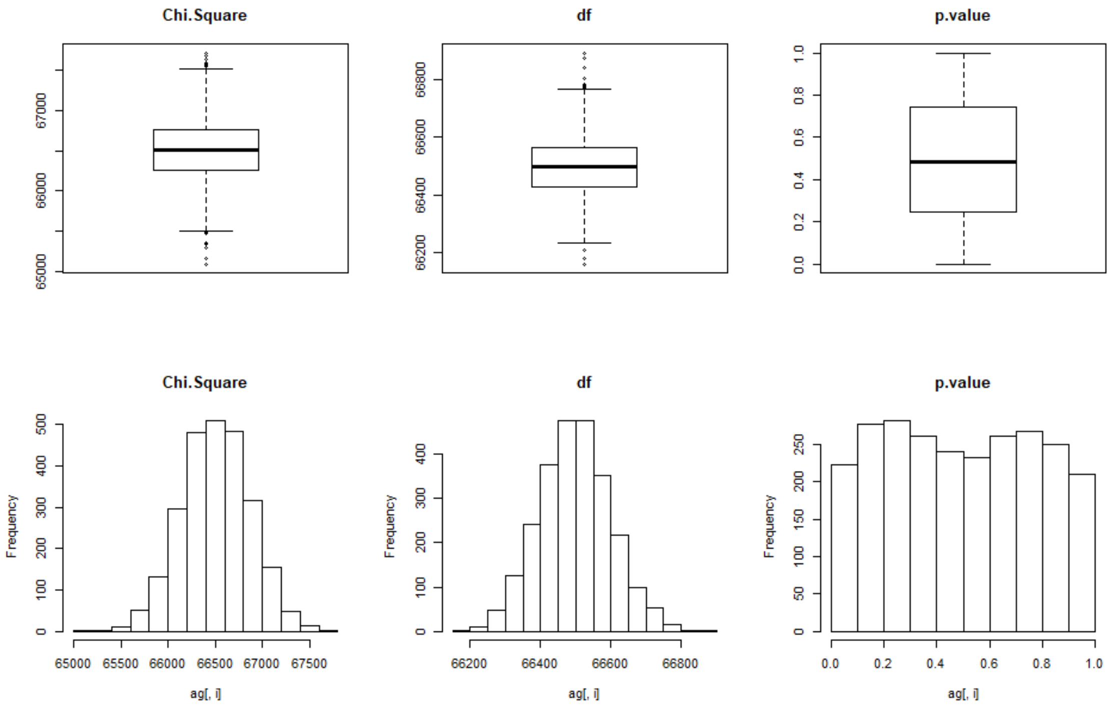
FigureA5-25: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Desert Uplands Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



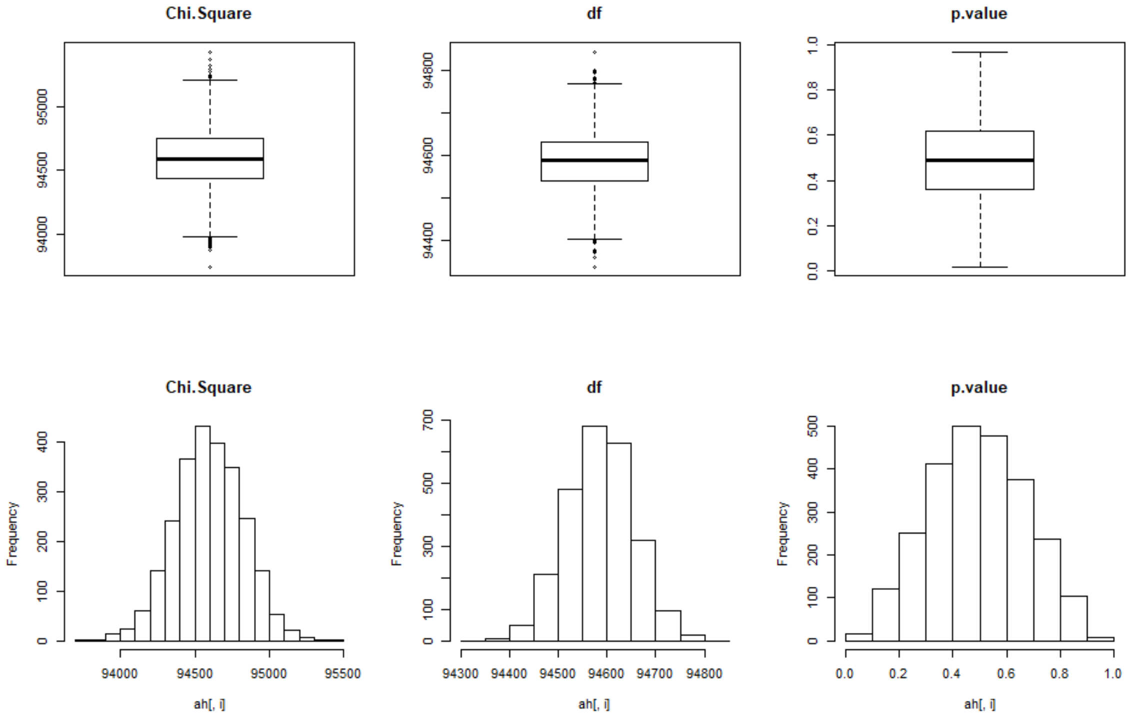
FigureA5-26: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Einasleigh Uplands Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



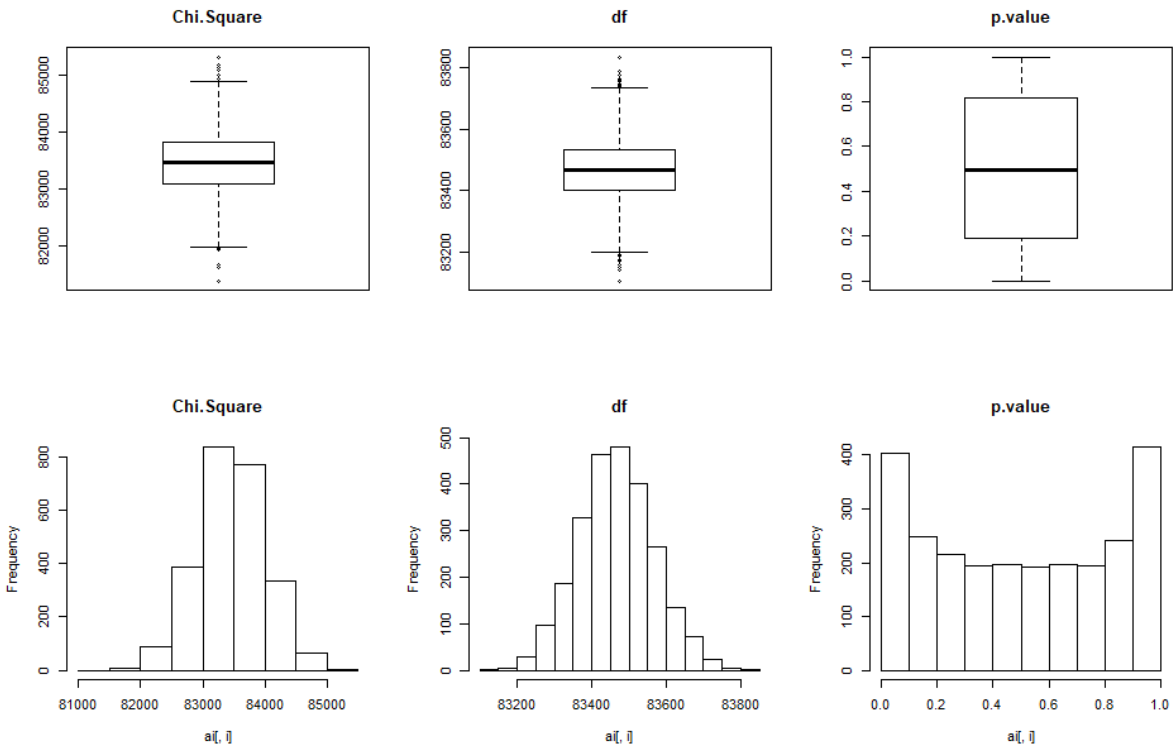
FigureA5-27: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Mulga Lands Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



FigureA5-28: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the New England Tablelands Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.



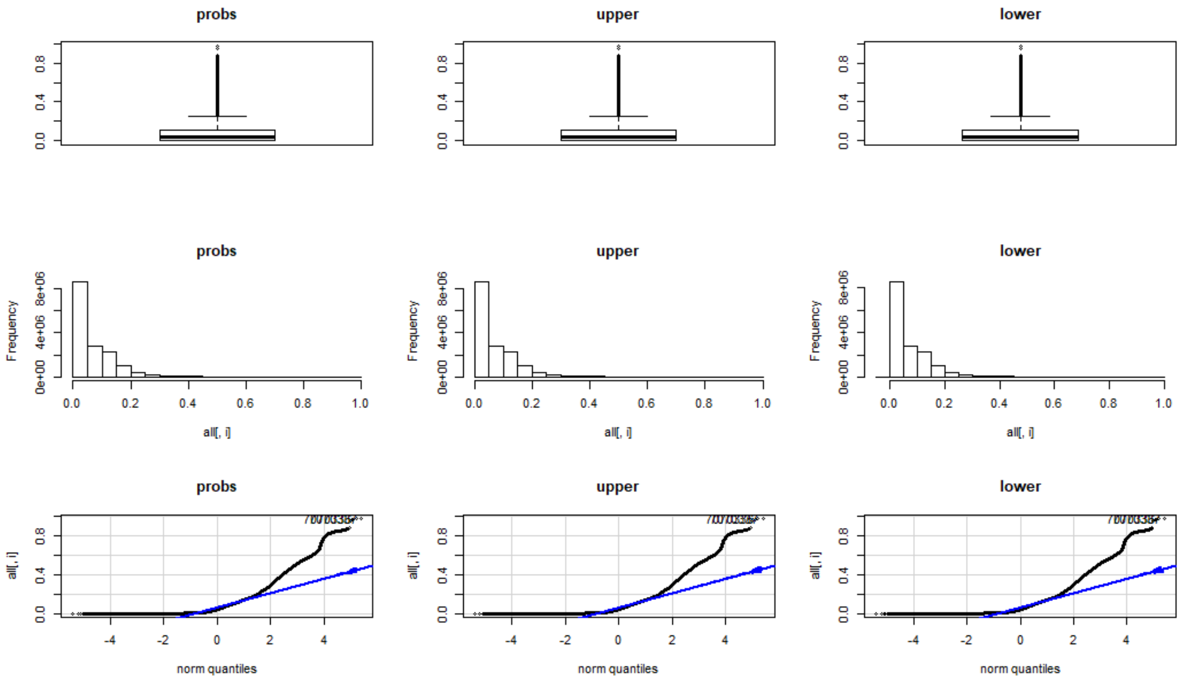
FigureA5-29: Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Southeast Queensland Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times,



FigureA5- 30 Boxplots and histograms for Chi-squared, degrees of freedom (df) and p.values for the Wet Tropics Bioregion. Values were calculated using a custom function in R which simulated a Pearson's Chi-squared test for 100,000 randomly sampled rows 2,500 times.

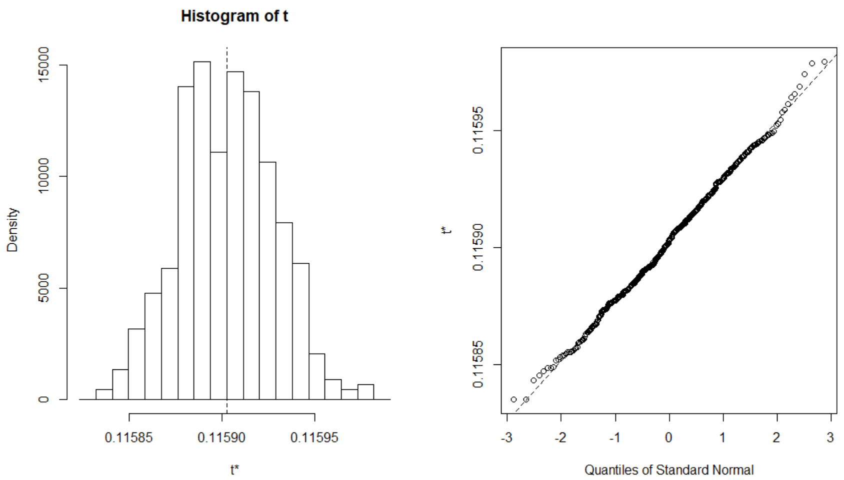
A5.4 Bootstrapping

I created boxplots, histograms and quantile-quantile plots of the predicted values finding that the distribution of these values was not normally distributed (**Figure A5-31**). Predicted values were left-skewed, indicating that there were more pixels with a low probability of being cleared than there were pixels with a probability of being cleared. This is demonstrated in the below plot as per the outliers in the boxplots, left tails in the histogram and the deviation from a straight line in the QQ plots. To calculate standard error for non-normally distributed data, I used a bootstrapping approach (Carpenter and Bithell 2000).

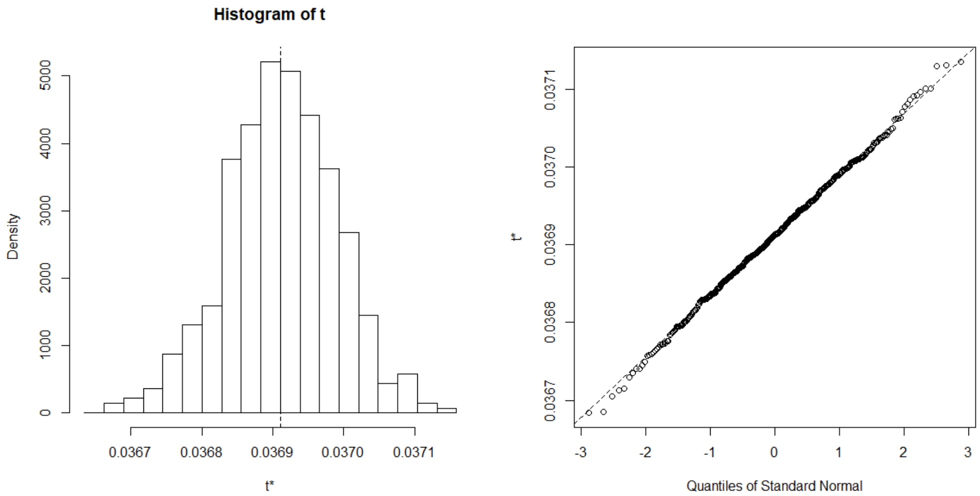


FigureA5- 31: Boxplots (top), histograms, and quantile-quantile plots for predicted values (probs). After using a bootstrapped approach for each bioregion, the upper and lower confidence intervals were calculated and then combined into a single dataframe.

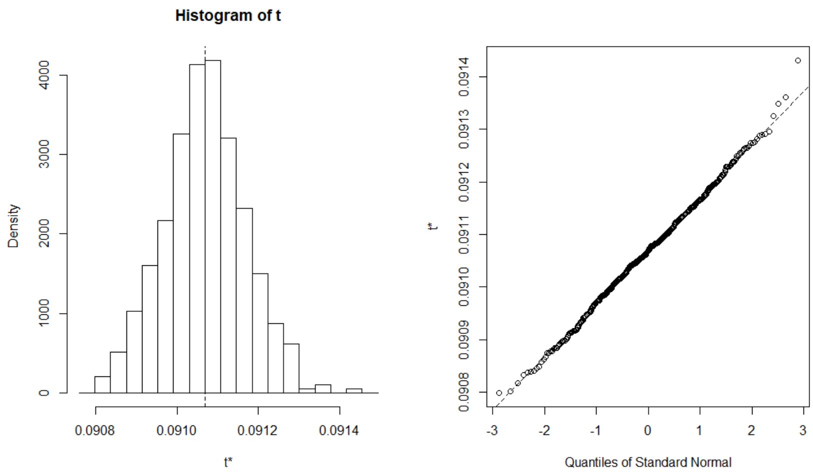
For each bioregion. The goal here is to ensure that the bootstrapped means are normally distributed. The bootstrapped procedure extracted 100,000 values of the bioregion's data and calculated the means of this sample. The extraction and averaging was completed 500 times. For quality checks, I created boxplots and histograms of the re-sampled (bootstrapped) means **(Figures A5-32 to Figures A5-39).**



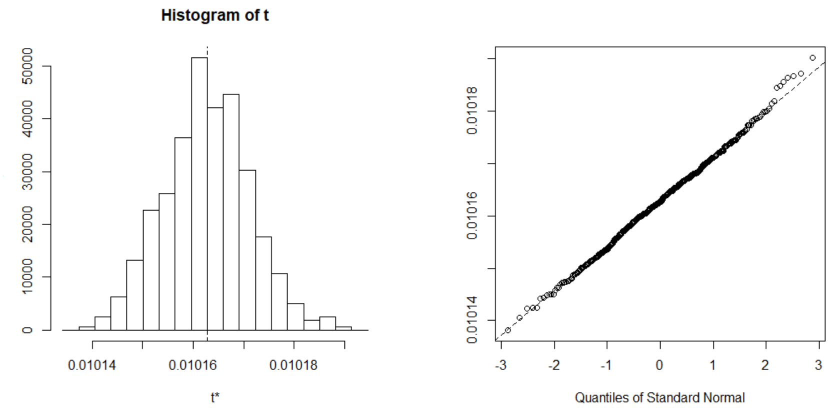
FigureA5-32: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for th Brigalow Belt showing a normal distribution of the predicted mean values.



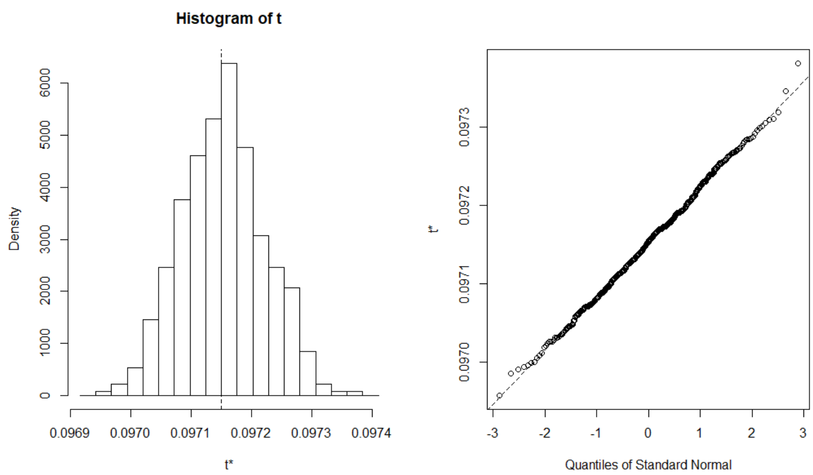
FigureA5-33: Histogram (left) and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Central Queensland Coast showing a normal distribution of the predicted mean values.



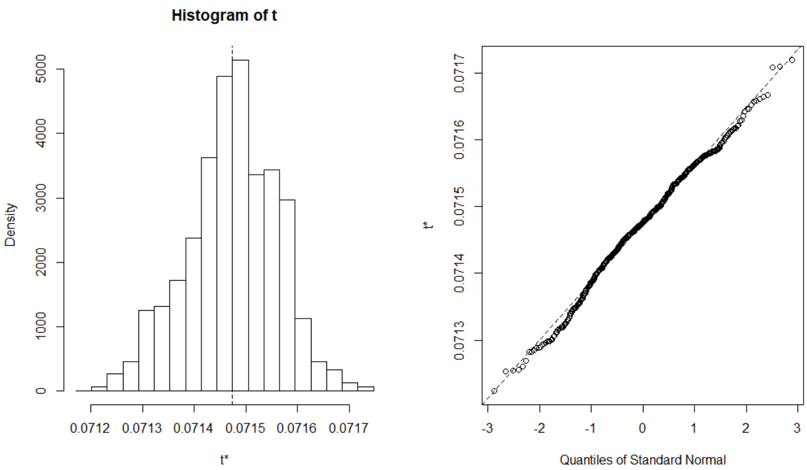
FigureA5-34: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Desert Uplands showing a normal distribution of the predicted mean values.



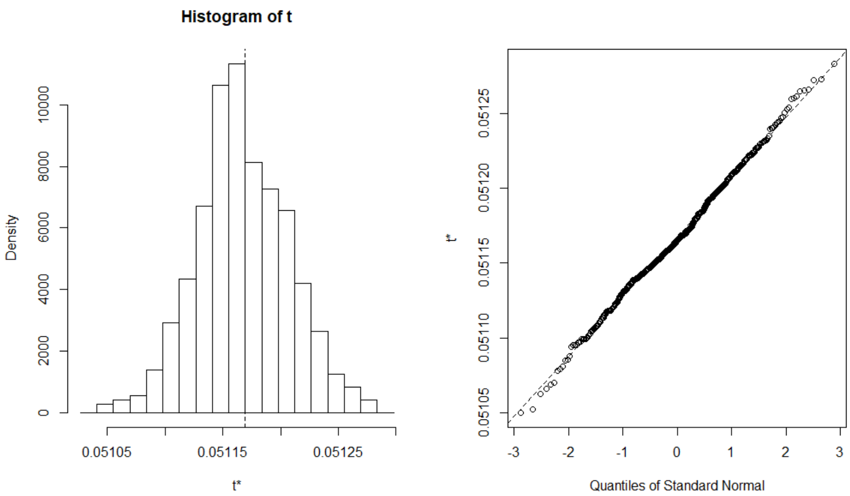
FigureA5-35: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Einasleigh Uplands showing a normal distribution of the predicted mean values.



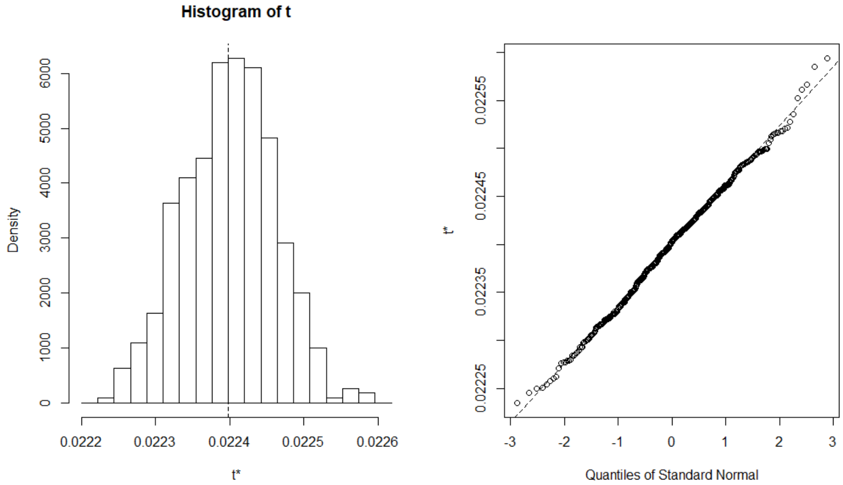
FigureA5-36: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Mulga Lands showing a normal distribution of the predicted mean values.



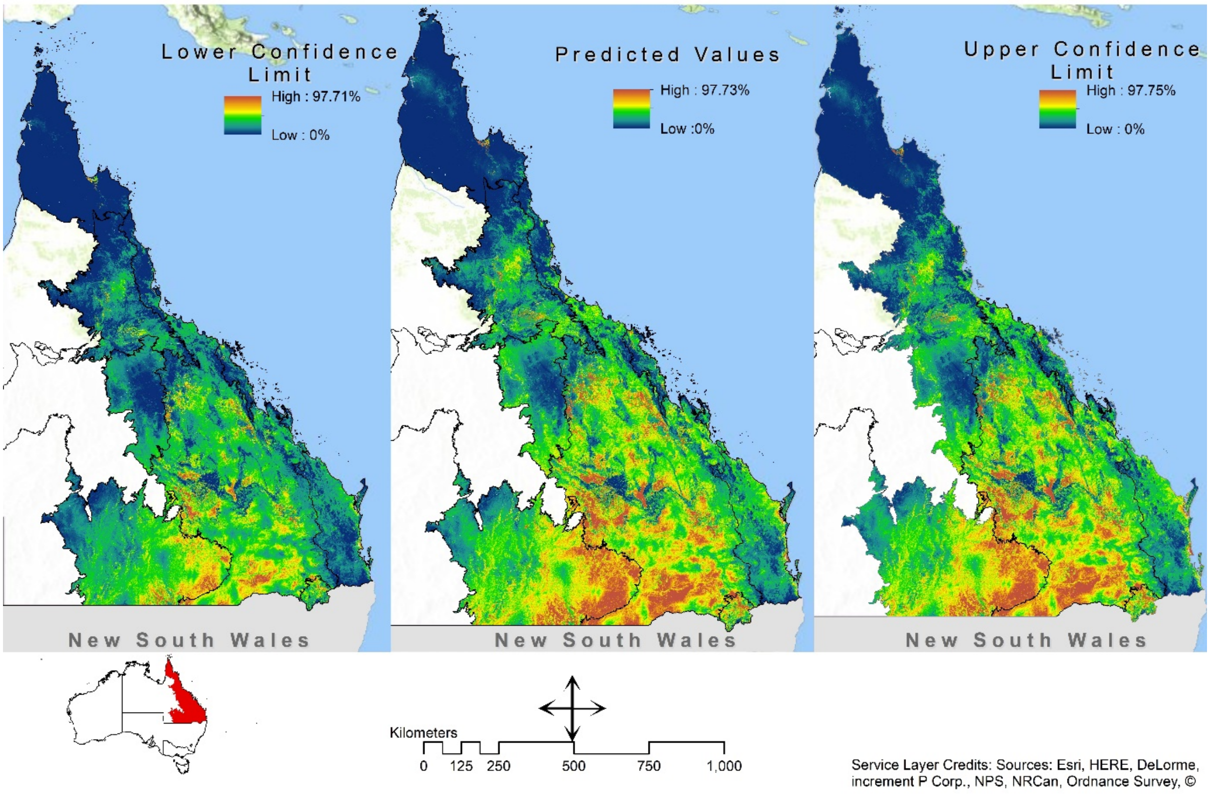
FigureA5-37: Histogram (left), and quantile-quantile plots for bootstrap sampled predicted values (probs) for the New England Tablelands showing a normal distribution of the predicted mean values.



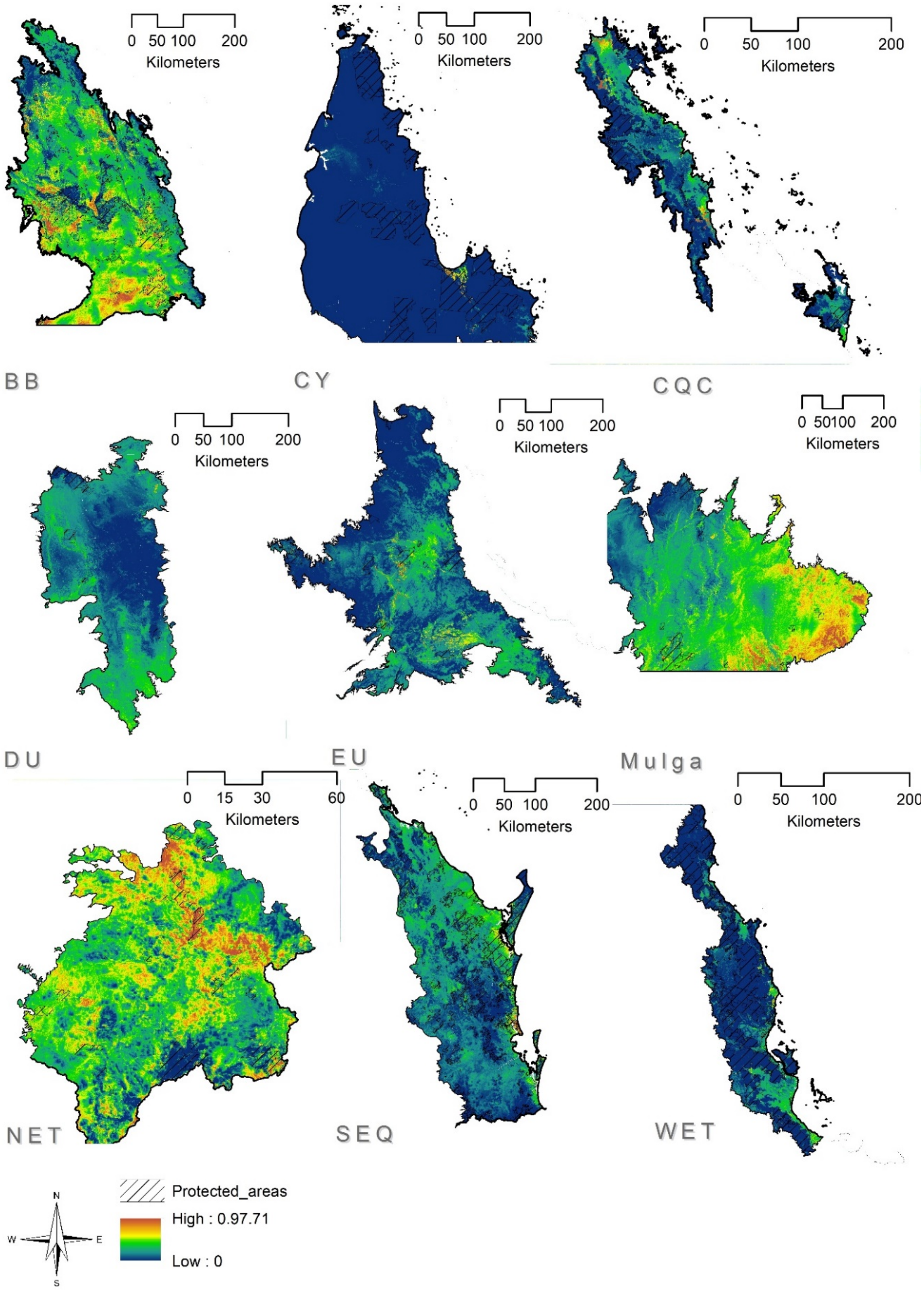
FigureA5-38: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Southeast Queensland showing a normal distribution of the predicted mean values.



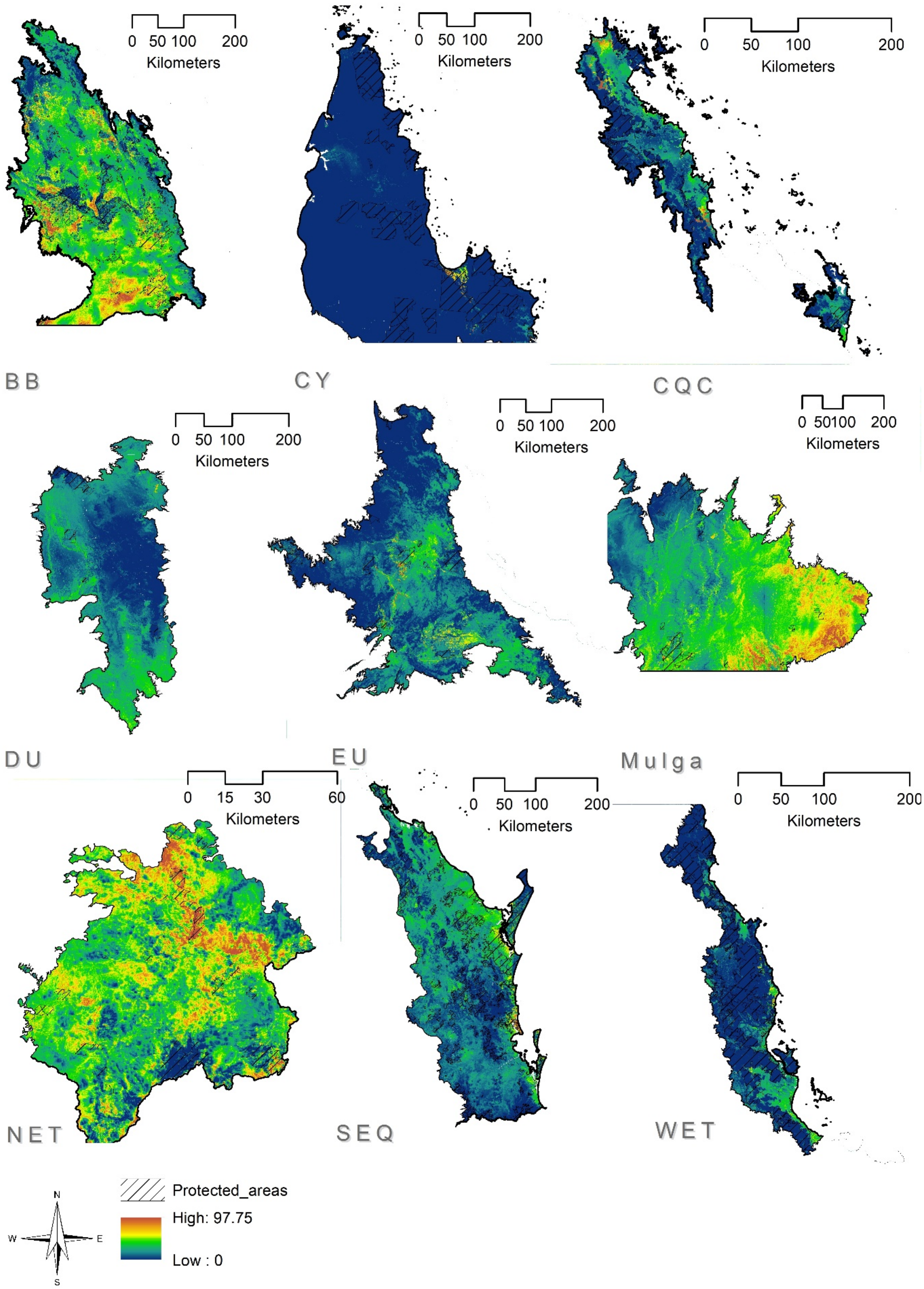
FigureA5- 39: Histogram (left),and quantile-quantile plots for bootstrap sampled predicted values (probs) for the Wet Tropics showing a normal distribution of the predicted mean values.



FigureA5- 40: Three maps of the study region showing the predicted probability that each pixel will be clearing according to the lowest estimate (derived from the lower confidence band), the predicted values from the model, and the highest estimate (derived from the upper confidence band).



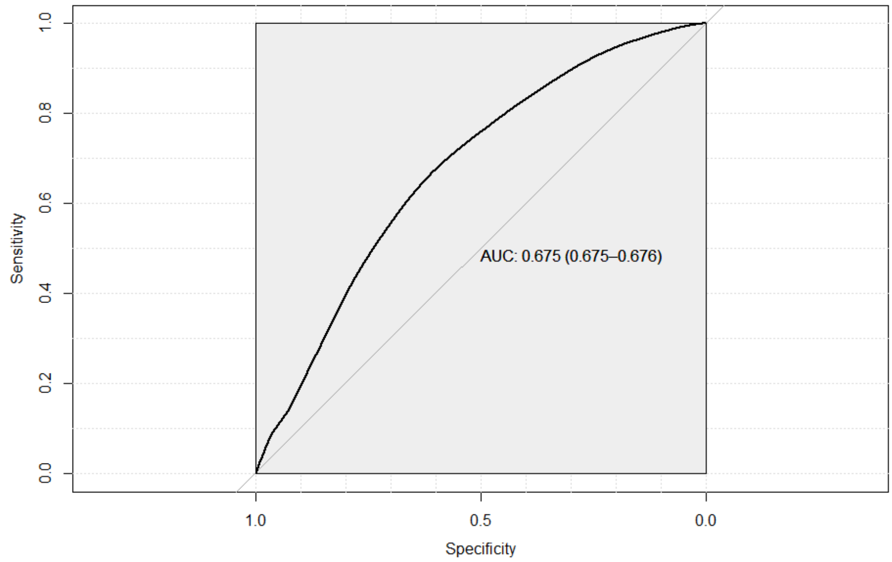
FigureA5- 41: Maps of the lower confidence interval per pixel (*ie* the lowest likely estimate that clearing will occur per pixel for each bioregion in the study area.



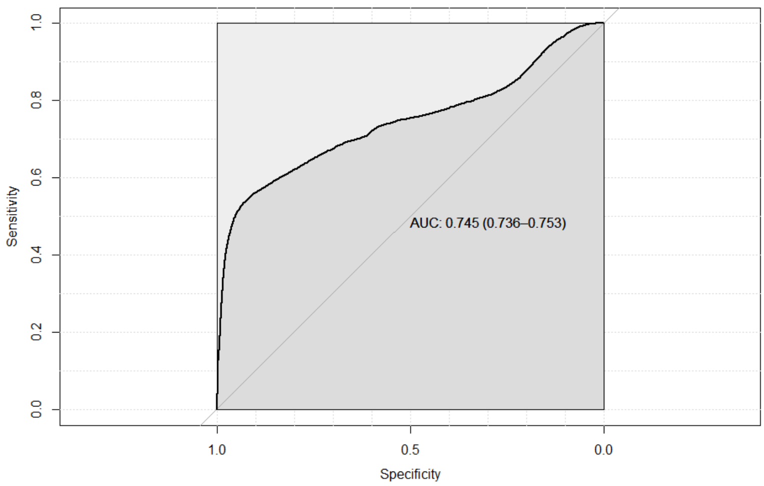
FigureA5-42: Maps of the upper confidence interval per pixel (*ie* the highest likely estimate that clearing will occur per pixel for each bioregion in the study).

A5.5 ROC curves and AUC values

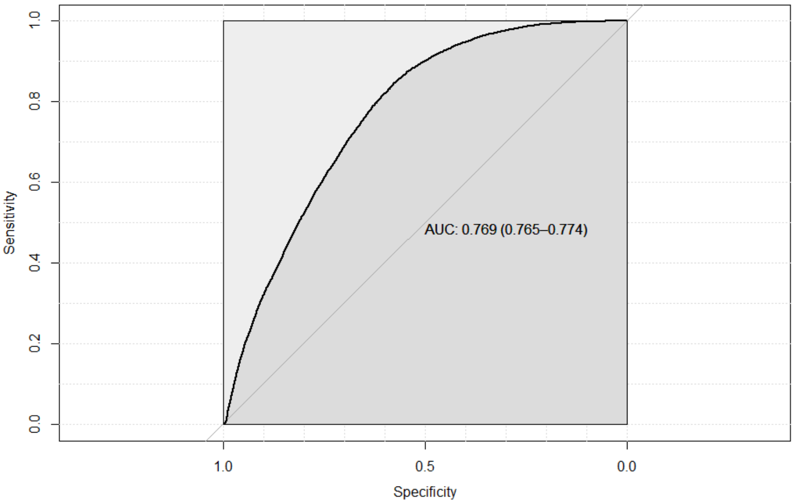
The graphs presented here show the receiving operating characteristic (ROC). The ROC is a graph illustrating the diagnostic ability of binary classification mode and is used as a performance measurement tool (Narkhede 2018). The AUC is a concordance statistic also used to discriminate how well the model accurately classifies predicted categories into the appropriate class (“1” or “0”). That is, high AUC values indicate that the model is better are predicting with an actual value of “0” with the predicted value of “0” and likewise “1s” as “1s.” In the context of this study, the AUC statistic measures how accurately the model truly predicted cleared and uncleared areas.



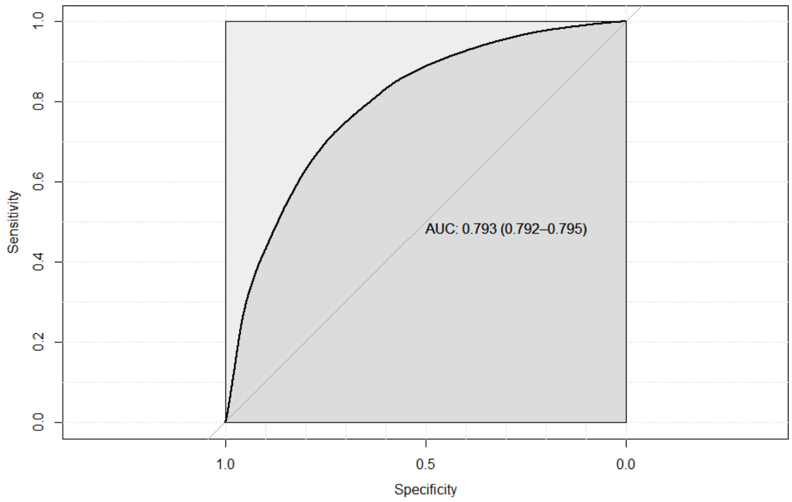
FigureA5-43: Area under the operating characteristic curves for the Brigalow Belt bioregion. The AUC value of 0.675 is an acceptable threshold for model fit.



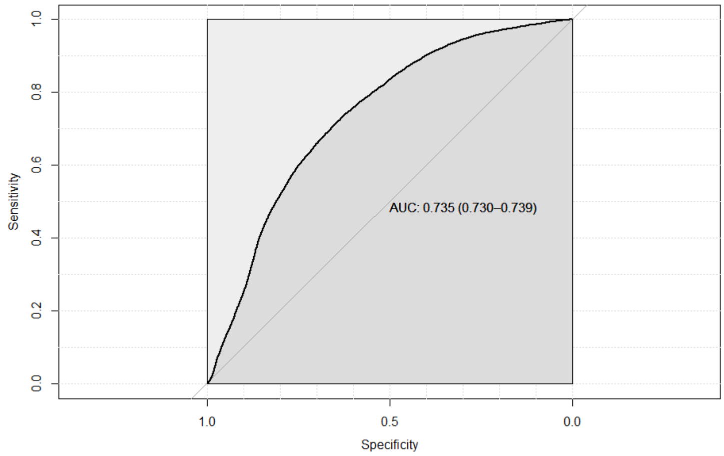
FigureA5-44: Area under the operating characteristic curves for Cape York bioregion. The AUC value of 0.745 is an acceptable threshold for model fit.



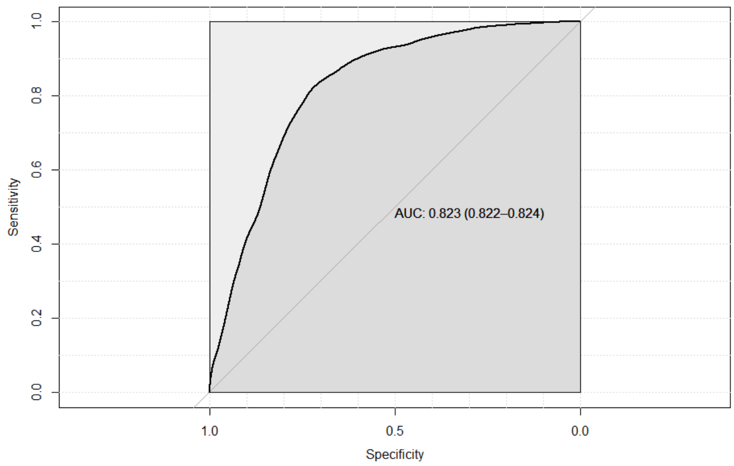
FigureA5-45: Area under the operating characteristic curves for the Central Queensland Coast bioregion. The AUC value of 0.769 is an acceptable threshold for model fit.



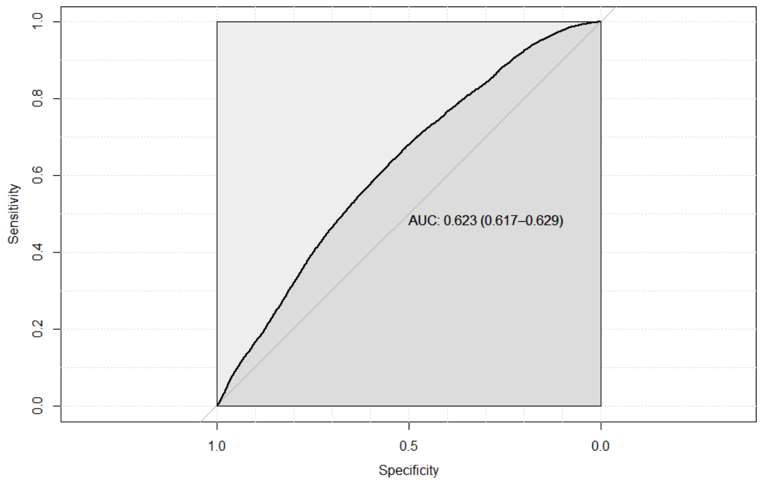
FigureA5-46: Area under the operating characteristic curves for the Desert Uplands bioregion. The AUC value of 0.793 is an acceptable threshold for model fit.



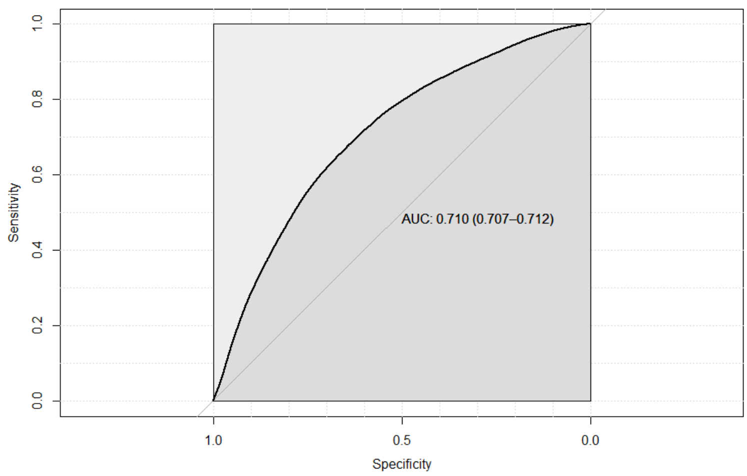
FigureA5-47: Area under the operating characteristic curves for the Einasleigh Uplands bioregion. The AUC value of 0.735 is an acceptable threshold for model fit.



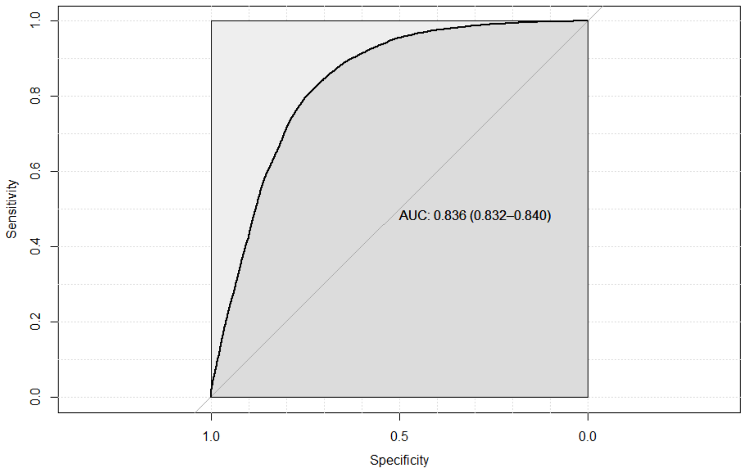
FigureA5-48: Area under the operating characteristic curves for the Mulga Lands bioregion. The AUC value of 0.823 is an acceptable threshold for model fit.



FigureA5-49: Area under the operating characteristic curves for the New England Tablelands bioregion. The AUC value of 0.675 is an acceptable threshold for model fit.



FigureA5-50: Area under the operating characteristic curves for the Southeast Queensland bioregion. The AUC value of 0.710 is an acceptable threshold for model fit.



FigureA5-51: Area under the operating characteristic curves for the Wet Tropics bioregion. The AUC value of 0.836 is an acceptable threshold for model fit.

5.6 Regional ecosystems likely to change status in the likely scenario

Table A5-1: Regional ecosystems likely to change status in the likely scenario (*ie* if all probability values above the mean are considered "high" (likely). In this table, we present the short description of the ecosystem as per the regional ecosystem description database ((Queensland Herbarium 2019)), the regional ecosystem's estimated historic extent (Total_Area_preclear), it's current extent (RemnantArea_2018), the extent to which the regional ecosystem overlaps with areas with the probability of clearing accordig to the likely scenario (PotentialArea_reupper), the percent of the regional ecosystem currently in protected areas, its current vegetation management status, and its predicted vegetation management status.

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
11.3.2	Eucalyptus populnea woodland on alluvial plains	1956297	512500.3	412081.5	12270.66	0.627239	Of concern	Endangered
6.7.12	Acacia aneura +/- Eucalyptus populnea +/- E. melanophloia +/- Eremophila gilesii subsp. gilesii tall shrubland on residuals	1463346	1204050	908266.3	15340.82	1.048339	Least concern	Of concern
6.5.15	Acacia aneura, Eucalyptus populnea +/- Eremophila sturtii tall open shrubland on sand plains	1093954	976202.3	754319.6	3919.693	0.358305	Least concern	Of concern
11.5.3	Eucalyptus populnea +/- E. melanophloia +/- Corymbia clarksoniana woodland on Cainozoic sand plains and/or remnant surfaces	991367.4	376111.6	200298.1	63.61568	0.006417	Least concern	Of concern
11.3.3	Eucalyptus coolabah woodland on alluvial plains	941908.5	275005.6	212955.2	0.01602	1.7E-06	Of concern	Endangered
6.5.7	Acacia aneura, Eucalyptus populnea +/- E. intertexta low woodland on run-on areas	842845.6	490925.9	434139.4	37803.44	4.485216	Least concern	Endangered
11.3.25	Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines	806866.3	519800.8	352363.8	4267.807	0.528936	Least concern	Of concern
11.5.1	Eucalyptus crebra and/or E. populnea, Callitris glaucophylla, Angophora leiocarpa, Allocasuarina luehmannii woodland on Cainozoic sand plains and/or remnant surfaces	790401.9	488053.1	482903.5	0	0	Least concern	Endangered
6.5.1	Acacia aneura, Eucalyptus populnea, E. melanophloia open forest on undulating lowlands	741722.9	262086.9	260418.4	9023.618	1.216575	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
11.8.5	Eucalyptus orgadophila open woodland on Cainozoic igneous rocks	641909.5	351950.1	204386.7	62.61238	0.009754	Least concern	Of concern
6.5.3	Eucalyptus populnea, Acacia aneura +/- Eremophila mitchellii woodland within A. aneura communities	638037	190880.3	183989.9	7009.228	1.098561	Of concern	Endangered
11.8.11	Dichanthium sericeum grassland on Cainozoic igneous rocks	614011.2	175060.5	161725.8	0	0	Of concern	Endangered
6.5.2	Eucalyptus populnea, Acacia aneura and/or E. melanophloia woodland on Quaternary sediments	603681.8	192466.9	190932.2	6686.945	1.107694	Of concern	Endangered
11.5.13	Eucalyptus populnea +/- Acacia aneura +/- E. melanophloia woodland on Cainozoic sand plains and/or remnant surfaces	580371.9	95484.09	94185.34	572.2764	0.098605	Of concern	Endangered
11.10.11	Eucalyptus populnea, E. melanophloia +/- Callitris glaucophylla woodland on coarse-grained sedimentary rocks	549499.9	326779.1	299180.6	12802.24	2.329798	Least concern	Endangered
6.5.8	Acacia aneura, Eucalyptus populnea +/- Eremophila gilesii subsp. gilesii low woodland	523326.2	443880.7	374502.7	727.7888	0.13907	Least concern	Of concern
11.9.7	Eucalyptus populnea, Eremophila mitchellii shrubby woodland on fine-grained sedimentary rocks	519633	104768.5	79937.45	1664.156	0.320256	Of concern	Endangered
11.10.9	Callitris glaucophylla woodland on coarse-grained sedimentary rocks	519418.8	383265.2	333099	8880.012	1.709606	Least concern	Endangered
11.9.10	Eucalyptus populnea open forest with a secondary tree layer of Acacia harpophylla and sometimes Casuarina cristata on fine-grained sedimentary rocks	492353.5	78481.34	65112.9	2645.932	0.537405	Of concern	Endangered
11.12.2	Eucalyptus melanophloia woodland on igneous rocks	478180.3	191986.5	57661.08	0	0	Least concern	Of concern
11.7.6	Corymbia citriodora or Eucalyptus crebra woodland on Cainozoic lateritic duricrust	423562.8	343188	277571.6	0	0	Least concern	Of concern
6.3.4	Acacia cambagei +/- Eucalyptus ochrophloia woodland on alluvium	410204.9	353769.7	339157.5	4232.434	1.031785	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
6.3.7	Eucalyptus coolabah, Acacia stenophylla low open woodland on alluvium	402469.1	379511.1	375699.2	8161.908	2.027959	Least concern	Endangered
11.10.7	Eucalyptus crebra woodland on coarse-grained sedimentary rocks	399714.4	291344	169678	3402.047	0.85112	Least concern	Of concern
11.5.5	Eucalyptus melanophloia, Callitris glaucophylla woodland on Cainozoic sand plains and/or remnant surfaces. Deep red sands	391314.6	135353.8	126202.4	1526.946	0.390209	Least concern	Endangered
11.9.2	Eucalyptus melanophloia +/- E. orgadophila woodland on fine-grained sedimentary rocks	378989.8	143517	85142.74	1764.573	0.465599	Least concern	Of concern
11.5.2	Eucalyptus crebra, Corymbia spp., with E. moluccana woodland on lower slopes of Cainozoic sand plains and/or remnant surfaces	366309.5	193021.7	139526.6	0	0	Least concern	Of concern
6.3.18	Eucalyptus populnea +/- Eremophila mitchellii +/- Acacia aneura +/- Eucalyptus melanophloia woodland on flat alluvial plains	360479.7	191290	180585	11254.14	3.121991	Least concern	Endangered
11.7.4	Eucalyptus decorticans and/or Eucalyptus spp., Corymbia spp., Acacia spp., Lysicarpus angustifolius woodland on Cainozoic lateritic duricrust	356834.9	230814.5	199200.8	0	0	Least concern	Endangered
6.3.15	Astrebla lappacea, A. pectinata +/- A. elymoides grassland on alluvium	329342.2	323534.2	321247.5	6620.145	2.010111	Least concern	Endangered
6.5.18	Acacia aneura +/- Eucalyptus populnea +/- E. melanophloia +/- Eremophila mitchellii low open woodland on plains	312170.6	181232.9	126434.8	1687.64	0.540614	Least concern	Of concern
6.4.3	Eucalyptus populnea, Casuarina cristata or Acacia harpophylla +/- Geijera parviflora woodland on clay plains	305948.9	39133.87	38987.98	1418.839	0.46375	Of concern	Endangered
6.5.13	Acacia aneura +/- Eucalyptus populnea +/- E. melanophloia +/- Brachychiton populneus low woodland on sand plains	298623	134745.1	133550.5	16082.22	5.385458	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
11.9.11	Acacia harpophylla shrubland on fine-grained sedimentary rocks	287465.4	53264.11	44418.93	2444.655	0.850417	Of concern	Endangered
6.5.10	Acacia aneura +/- Eucalyptus populnea +/- Grevillea striata, A. excelsa, Hakea ivoryi low woodland on sand plains	279517.6	193073	191637.8	12482.28	4.465652	Least concern	Endangered
6.5.17	Eucalyptus populnea +/- E. melanophloia +/- Callitris glaucophylla +/- Acacia aneura woodland on sand plains	275420.1	72688.03	72671.35	944.3396	0.342872	Of concern	Endangered
11.9.3	Dichanthium spp., Astrebla spp. grassland on fine-grained sedimentary rocks	272178.6	154083.6	147095.2	11143.42	4.094159	Least concern	Endangered
11.3.17	Eucalyptus populnea woodland with Acacia harpophylla and/or Casuarina cristata on alluvial plains	263856.9	33972.8	32304.22	88.86091	0.033678	Of concern	Endangered
11.9.9	Eucalyptus crebra woodland on fine-grained sedimentary rocks	260646.3	129106.1	83272.9	0	0	Least concern	Of concern
6.5.5	Eucalyptus populnea +/- E. intertexta +/- Acacia aneura +/- Callitris glaucophylla woodland on Quaternary sediments	252083.4	59279.96	59279.94	726.1898	0.288075	Of concern	Endangered
6.3.21	Acacia aneura, A. excelsa and/or Geijera parviflora low woodland on low alluvial sand dunes	246415.9	221855	219621.9	12594.76	5.11118	Least concern	Endangered
11.3.19	Callitris glaucophylla, Corymbia spp. and/or Eucalyptus melanophloia open forest to woodland on Cainozoic alluvial plains	240955.5	92294.02	88650.26	2289.776	0.95029	Least concern	Endangered
10.5.12	Eucalyptus populnea open woodland on sand plains	238001.4	141188.5	88837	3976.582	1.670823	Least concern	Of concern
6.5.9	Acacia aneura, Eucalyptus populnea +/- E. melanophloia shrubby low woodland on Quaternary sediments	236089.8	79584.12	75290.14	3669.674	1.554355	Least concern	Endangered
11.5.20	Eucalyptus moluccana and/or E. microcarpa and/or E. woollsiana +/- E. crebra woodland on Cainozoic sand plains	233802.5	153060	131535.4	0	0	Least concern	Endangered
12.5.4	Eucalyptus latisinensis +/- Corymbia intermedia, C. trachyphloia subsp.	213641.7	103619.7	85459.26	0	0	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	trachyphloia, Angophora leiocarpa, Eucalyptus exserta woodland on complex of remnant Tertiary surfaces and Cainozoic and Mesozoic sediments							
11.7.1	Acacia harpophylla and/or Casuarina cristata and Eucalyptus thozetiana or E. microcarpa woodland on lower scarp slopes on Cainozoic lateritic duricrust	203796.7	79026.51	45341.95	1318.06	0.646752	Least concern	Of concern
11.7.7	Eucalyptus fibrosa subsp. nubilis +/- Corymbia spp. +/- Eucalyptus spp. woodland on Cainozoic lateritic duricrust	203764.3	174902.9	169931.3	0	0	Least concern	Endangered
11.4.2	Eucalyptus spp. and/or Corymbia spp. grassy or shrubby woodland on Cainozoic clay plains	198502.4	34926.37	28582.56	0	0	Of concern	Endangered
11.3.39	Eucalyptus melanophloia +/- E. chloroclada open woodland on undulating plains and valleys with sandy soils	191422.9	141036.9	90104.37	1888.78	0.986706	Least concern	Of concern
11.3.35	Eucalyptus platyphylla, Corymbia clarksoniana woodland on alluvial plains	185317.2	110668	56682.93	0	0	Least concern	Of concern
6.6.1	Atalaya hemiglauca +/- Acacia aneura +/- Acacia spp. +/- Corymbia terminalis tall open shrubland on low dunes over alluvium	174343.8	172556.1	121527.3	1462.992	0.839142	Least concern	Of concern
11.3.5	Acacia cambagei woodland on alluvial plains	165769.9	52025.17	26009.99	0	0	Least concern	Of concern
11.12.3	Eucalyptus crebra, E. tereticornis, Angophora leiocarpa woodland on igneous rocks especially granite	161595.1	56530.73	18447.3	0	0	Least concern	Of concern
10.3.27	Eucalyptus populnea woodland to open woodland on alluvial plains	160270.3	65073.38	50038.54	707.1694	0.441235	Least concern	Endangered
8.3.5	Eucalyptus platyphylla and/or Lophostemon suaveolens and/or Corymbia clarksoniana woodland on alluvial plains	156387.4	21332.04	6454.032	0	0	Of concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
6.3.3	Eucalyptus camaldulensis +/- E. coolabah +/- E. populnea, Acacia stenophylla woodland on alluvium	153706.6	140909	123444.8	2148.858	1.398025	Least concern	Endangered
10.9.2	Acacia cambagei and/or Eucalyptus thozetiana low woodland to open woodland on calcareous sandstones	150907.9	109725.2	71528.45	14.32598	0.009493	Least concern	Of concern
11.10.6	Angophora leiocarpa, Callitris glaucophylla open woodland on coarse-grained sedimentary rocks. Broad valleys	150819.2	144995.4	107863.9	8756.195	5.805755	Least concern	Of concern
11.3.9	Eucalyptus platyphylla, Corymbia spp. woodland on alluvial plains	146205.3	63970.39	25361.33	0	0	Least concern	Of concern
11.5.4	Eucalyptus chloroclada, Callitris glaucophylla, C. endlicheri, Angophora leiocarpa woodland on Cainozoic sand plains and/or remnant surfaces	145393.4	110958.5	110283.4	0	0	Least concern	Endangered
6.3.11	Eleocharis pallens +/- short grasses +/- Eragrostis australasica open herbland on clays, associated with ephemeral lakes, billabongs and permanent waterholes	143933.9	136325.4	123272.3	5585.692	3.880734	Least concern	Endangered
11.3.18	Eucalyptus populnea, Callitris glaucophylla, Allocasuarina luehmannii shrubby woodland on alluvium	143025.1	80015.41	67711.73	2525.986	1.766114	Least concern	Endangered
11.3.7	Corymbia spp. woodland on alluvial plains	140874.2	63087.54	34926.89	0	0	Least concern	Of concern
6.5.11	Acacia aneura +/- Eucalyptus populnea low woodland on sand plains	136763.7	67670.37	66725.99	2679.865	1.959486	Least concern	Endangered
6.3.14	Astrebla spp., Dichanthium spp. open grassland on alluvium	131054.4	125112.2	108708.2	9271.899	7.074847	Least concern	Endangered
10.4.8	Astrebla squarrosa and Iseilema vaginiflorum +/- Dichanthium sericeum and Panicum laevinode open tussock grassland on Cainozoic lake beds	127995.6	119610.5	101256.4	0	0	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
11.3.26	Eucalyptus moluccana or E. microcarpa woodland to open forest on margins of alluvial plains	124114.6	45279.71	29347.3	65.32411	0.052632	Least concern	Of concern
6.6.2	Triodia mitchellii +/- T. marginata hummock grassland wooded with Eucalyptus melanophloia +/- Eucalyptus spp. and Acacia spp. on low dunes	119520.3	101913.2	84791.94	6270.972	5.246783	Least concern	Endangered
11.1.2	Samphire forbland on marine clay plains	119161.8	104866.7	84511.89	0	0	Least concern	Of concern
11.3.14	Eucalyptus spp., Angophora spp., Callitris spp. woodland on alluvial plains	107991.8	82586.37	82517.44	0	0	Least concern	Endangered
6.3.17	Callitris glaucophylla, Corymbia tessellaris, Acacia excelsa +/- C. clarksoniana open woodland on old alluvial dunes and sand plains	106222.7	46031.55	45957.97	2104.569	1.98128	Least concern	Endangered
10.9.6	Acacia cambagei low woodland to open woodland on Cretaceous sediments	105425.3	37067.62	11424.22	1501.957	1.424665	Least concern	Of concern
11.4.5	Acacia argyrodendron woodland on Cainozoic clay plains	102037.1	11861.95	3716.705	0	0	Of concern	Endangered
11.10.12	Eucalyptus populnea woodland on medium to coarse-grained sedimentary rocks	99716.39	46902.48	25376.12	0	0	Least concern	Of concern
13.11.8	Eucalyptus melliodora and/or Eucalyptus microcarpa/ E. moluccana woodland on metamorphics	99353.3	27132.07	18105.75	0	0	Of concern	Endangered
6.3.16	Callitris glaucophylla, Acacia excelsa, Geijera parviflora +/- Acacia aneura woodland on alluvial dunes	97871.66	85259.75	84562.87	5183.473	5.296194	Least concern	Endangered
4.9.17	Acacia harpophylla +/- A. cambagei low woodland on undulating clay plains	95471.29	12776.19	3591.727	483.0776	0.505993	Of concern	Endangered
11.3.15	Eucalyptus coolabah, Acacia stenophylla, Duma florulenta fringing open woodland on alluvial plains	90938.08	24024.43	23171.63	0	0	Of concern	Endangered
6.3.25	Acacia harpophylla and/or A. cambagei low woodland to woodland on alluvial plains	87234.22	59882.28	59120.71	323.133	0.37042	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
10.3.4	Acacia cambagei low open woodland to low woodland on alluvial plains	83539.05	35822.8	14337.24	239.1103	0.286226	Least concern	Of concern
6.7.5	Eucalyptus thozetiana or E. cambageana, Acacia harpophylla woodland on scarps	78804.53	33840.2	28110.77	6378.946	8.094644	Least concern	Endangered
6.3.24	Eucalyptus coolabah or E. populnea woodland on alluvial plains	78110.77	29528.99	29464.34	5074.422	6.496444	Least concern	Endangered
11.5.21	Corymbia bloxsomei +/- Callitris glaucophylla +/- Eucalyptus crebra +/- Angophora leiocarpa woodland on Cainozoic sand plains and/or remnant surfaces	78079.85	73112.36	72929.6	0	0	Least concern	Endangered
11.7.5	Shrubland on natural scalds on deeply weathered coarse-grained sedimentary rocks	75678.45	64501.77	55566.13	0	0	Least concern	Endangered
11.4.11	Dichanthium sericeum and Astrebla spp. grassland with patchy Acacia harpophylla or Eucalyptus coolabah on Cainozoic clay plains	74987.9	23905.09	18750.01	0	0	Of concern	Endangered
11.4.4	Dichanthium spp., Astrebla spp. grassland on Cainozoic clay plains	67801.27	24703.47	23124.27	0	0	Least concern	Endangered
11.9.13	Eucalyptus moluccana or E. microcarpa open forest on fine grained sedimentary rocks	66984.15	20634.64	14043.37	0	0	Of concern	Endangered
11.3.6	Eucalyptus melanophloia woodland on alluvial plains	65355.02	28947.18	19042.48	1867.769	2.857881	Least concern	Endangered
12.5.7	Corymbia citriodora subsp. variegata +/- Eucalyptus portuensis or E. acmenoides, E. fibrosa subsp. fibrosa open forest on remnant Tertiary surfaces. Usually deep red soils	63697.86	30681.14	18179.46	0	0	Least concern	Of Concern
6.3.22	Acacia victoriae +/- Eucalyptus spp. tall open shrubland on old levees	62254.67	58418.88	58313.83	1405.333	2.257394	Least concern	Endangered
6.3.1	Eucalyptus camaldulensis woodland on alluvium within Acacia aneura associations	61781.06	46588.11	43694.24	4483.399	7.256916	Least concern	Endangered
6.7.11	Acacia aneura +/- Eucalyptus cambageana +/- E. thozetiana +/- Eremophila latrobei tall shrubland on residuals	61635.98	34235.32	22402.81	2252.692	3.654833	Least concern	Of Concern

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
12.11.18	Eucalyptus moluccana woodland on metamorphics +/- interbedded volcanics	61420.1	25219.23	7745.676	0	0	Least concern	Of concern
10.3.3	Acacia harpophylla and/or Eucalyptus cambageana low open woodland to open woodland on alluvial plains	60733.17	24980.78	11316.04	17.13376	0.028212	Least concern	Of concern
6.9.2	Acacia tephrina +/- A. cambagei low open woodland on undulating plains over Cretaceous sediments	59272.71	59064.46	48877.42	0	0	Least concern	Of concern
12.5.12	Eucalyptus racemosa subsp. racemosa, E. latisinensis +/- Corymbia gummifera, C. intermedia, E. bancroftii woodland with heathy understorey on remnant Tertiary surfaces	58022.07	16353.33	13908.88	0	0	Of concern	Endangered
6.7.1	Acacia catenulata +/- A. shirleyi +/- Eucalyptus spp. open scrub on crests and slopes	55259.43	31260.82	13290.11	1918.811	3.472369	Least concern	Of concern
12.9-10.4	Eucalyptus racemosa subsp. racemosa woodland on sedimentary rocks	53873.14	20525.21	15322.82	0	0	Least concern	Endangered
11.3.37	Eucalyptus coolabah fringing woodland on alluvial plains	53028	30374.92	25695.38	0	0	Least concern	Endangered
11.3.27	Freshwater wetlands	52277.38	49835.44	40878.71	42.16551	0.080657	Least concern	Endangered
6.3.9	Eucalyptus coolabah, E. populnea open woodland on alluvium	51679.27	48655.53	47325.68	1968.7	3.809458	Least concern	Endangered
11.3.20	Forb and/or grassland +/- scattered Atalaya hemiglauca, Flindersia maculosa, Acacia spp. on alluvial plains	47985.81	25866.52	25395.43	0	0	Least concern	Endangered
12.3.5	Melaleuca quinquenervia open forest on coastal alluvium	46279.94	20594.94	18034.12	0	0	Least concern	Endangered
11.3.12	Melaleuca viridiflora M. argentea +/- M. dealbata woodland on alluvial plains	45970.05	28480.17	19901.61	0	0	Least concern	Endangered
6.5.6	Acacia aneura, Eucalyptus populnea low woodland on run-on plains	45836.24	28774.84	25945.06	2166.48	4.726566	Least concern	Endangered
11.5.15	Semi-evergreen vine thicket on Cainozoic sand plains and/or remnant surfaces	44442.29	14584.63	2953.159	0	0	Least concern	Of Concern

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
11.3.31	Ophiuros exaltatus, Dichanthium spp. grassland on alluvial plains	43665.92	18199.59	15707.84	0	0	Least concern	Endangered
8.12.20	Eucalyptus drepanophylla and/or E. platyphylla +/- Corymbia spp. +/- E. crebra woodland on low gently undulating landscapes on Mesozoic to Proterozoic igneous rocks	43438.82	17001.12	4362.864	0	0	Least concern	Of concern
6.5.19	Callitris glaucophylla +/- Angophora melanoxylon +/- Eucalyptus melanophloia +/- E. chloroclada open woodland on Cainozoic sediments derived from old alluvial levees and dunes	43090.57	19400.27	19379.38	0	0	Least concern	Endangered
11.1.1	Sporobolus virginicus grassland on marine clay plains	40117.09	20132.36	17090.05	0	0	Least concern	Endangered
7.3.8	Melaleuca viridiflora +/- Eucalyptus spp. +/- Lophostemon suaveolens open forest to open woodland on poorly drained alluvial plains	39109.94	15088.66	11056.45	0	0	Least concern	Endangered
7.3.16	Eucalyptus platyphylla woodland to open forest on alluvial plains	37436.43	16152.57	6738.201	0	0	Least concern	Endangered
11.3.16	Eucalyptus largiflorens +/- Acacia cambagei +/- A. harpophylla woodland to low open woodland on alluvial plains	37005.59	14382.41	13940.59	0	0	Least concern	Endangered
6.3.12	Acacia omalophylla +/- A. microsperma +/- Eucalyptus coolabah tall open shrubland on alluvium	36825.64	31620.91	31269.06	3375.097	9.165072	Least concern	Endangered
11.9.8	Macropteranthes leichhardtii thicket on fine grained sedimentary rocks	36062.68	11957.67	2737.988	676.1258	1.874863	Least concern	Endangered
10.3.12	Corymbia dallachiana and C. plena or C. terminalis woodland to open woodland on sandy alluvial terraces (eastern)	33863.8	25151.18	14122.82	559.9074	1.65341	Least concern	Of concern
7.3.45	Corymbia clarksoniana +/- C. tessellaris +/- E. drepanophylla open forest to open woodland on alluvial plains	33577.2	11414.49	6358.488	0	0	Least concern	Endangered
12.3.6	Melaleuca quinquenervia +/- Eucalyptus tereticornis, Lophostemon	33157	12988.93	9602.916	0	0	Least concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	suaveolens, Corymbia intermedia open forest on coastal alluvial plains							
11.5.7	Eucalyptus acmenoides, Angophora leiocarpa open forest on Cainozoic sand plains and/or remnants	32656.78	29910.65	24129.51	0	0	Least concern	Endangered
12.2.7	Melaleuca quinquenervia or rarely M. dealbata open forest on sand plains	32159.52	19240.61	13580.51	0	0	Least concern	Endangered
10.9.3	Acacia harpophylla and/or Eucalyptus cambageana open woodland to woodland on Mesozoic sediments	30355.6	15354.97	5742.346	0	0	Least concern	Of Concern
12.9-10.14	Eucalyptus pilularis tall open forest on sedimentary rocks	30196.82	13288.32	7322.349	0	0	Least concern	Endangered
12.11.24	Eucalyptus carnea, E. tindaliae, Corymbia intermedia +/- E. siderophloia or E. crebra woodland on metamorphics +/- interbedded volcanics	29376.23	14600.94	4776.441	0	0	Least concern	Of Concern
7.8.4	Simple to complex notophyll vine forest of cloudy wet highlands on basalt	28821.97	10284.89	0	0	0	Least concern	Of concern
6.7.2	Acacia microsperma open forest on upper and footslopes	28819.76	11586.24	11300.67	0	0	Least concern	Endangered
12.5.10	Eucalyptus latisinensis and/or Banksia aemula low open woodland on complex of remnant Tertiary surface and Tertiary sedimentary rocks	26762.27	16342.88	15846.34	0	0	Least concern	Endangered
11.3.32	Allocasuarina luehmannii open woodland on alluvial plains	26484.32	17201.02	8286.29	0	0	Least concern	Endangered
6.4.4	Acacia harpophylla and/or A. cambagei low woodland on Quaternary deposits overlying older sediments	25917.43	17438.16	14232.47	0	0	Least concern	Endangered
8.3.3	Melaleuca leucadendra and/or M. fluviatilis and/or Casuarina cunninghamiana +/- Syncarpia glomulifera open forest, on creek banks	25668.31	15698.44	5702.904	0	0	Least concern	Of Concern

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
12.9-10.16	Araucarian microphyll to notophyll vine forest on Cainozoic and Mesozoic sediments	24318.72	8867.405	1424.113	0	0	Of concern	Endangered
11.4.13	Eucalyptus orgadophila open woodland on Cainozoic clay plains	23291.8	11687.85	11442.3	0	0	Least concern	Endangered
12.3.13	Closed heathland on seasonally waterlogged alluvial plains usually near coast	22539.78	13891.79	13159.41	0	0	Least concern	Endangered
12.3.2	Eucalyptus grandis tall open forest on alluvial plains	22412.47	7639.122	5564.365	0	0	Of concern	Endangered
11.9.14	Lysiphyllum carronii, Atalaya hemiglauca +/- Eucalyptus melanophloia +/- Acacia excelsa open woodland	21473.54	8506.139	8304.172	0	0	Of concern	Endangered
11.3.36	Eucalyptus crebra and/or E. populnea and/or E. melanophloia on alluvial plains. Higher terraces	20176.45	8490.881	3372.187	0	0	Of concern	Endangered
13.11.5	Eucalyptus sideroxylon, E. fibrosa subsp. nubilis open forest on metamorphics	19982.83	11242.81	10344.5	0	0	Least concern	Endangered
13.11.6	Corymbia citriodora subsp. variegata open forest on metamorphics	19966.58	13550.47	9945.897	0	0	Least concern	Endangered
12.5.8	Eucalyptus hallii open woodland on complex of remnant Tertiary surface and Tertiary sedimentary rocks	19670.02	9381.617	8521.224	0	0	Of concern	Endangered
8.3.13	Eucalyptus tereticornis and/or Corymbia tessellaris and/or Melaleuca spp. woodland on alluvial and marine plains, often adjacent to estuarine areas	19454.42	6818.137	3754.284	0	0	Of concern	Endangered
11.11.20	Eucalyptus platyphylla woodland on old sedimentary rocks with varying degrees of metamorphism and folding. Lowlands	19438.22	11382.55	1335.449	0	0	Least concern	Of concern
12.3.12	Eucalyptus latisinensis or E. exserta, Melaleuca viridiflora var. viridiflora woodland on alluvial plains	18726.06	13950.23	6515.416	0	0	Least concern	Of Concern
12.11.25	Corymbia henryi and/or Eucalyptus fibrosa subsp. fibrosa +/- E. crebra, E. carnea, E. tindaliae woodland on	18113.33	8209.913	3510.51	0	0	Of concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	metamorphics +/- interbedded volcanics							
12.3.4	Melaleuca quinquenervia, Eucalyptus robusta woodland on coastal alluvium	18083.71	8390.266	8139.747	0	0	Of concern	Endangered
11.3.34	Acacia tephrina woodland on alluvial plains	16469.94	9170.509	4725.688	0	0	Of concern	Endangered
12.2.5	Corymbia intermedia +/- Lophostemon confertus +/- Banksia spp. +/- Callitris columellaris open forest on beach ridges usually in southern half of bioregion	16405.25	10966.06	7675.196	0	0	Least concern	Endangered
6.3.10	Tecticornia spp. open succulent shrubland on alluvium	16118.26	16118.26	15755.66	0	0	Least concern	Endangered
6.7.16	Acacia clivicola, Eucalyptus exserta open shrubland on colluvials associated with residuals	15974.15	11375.88	7496.555	152.1118	0.952237	Least concern	Endangered
10.3.7	Astrebla spp., Iseilema vaginiflorum and/or Dichanthium fecundum or Bothriochloa ewartiana tussock grassland on alluvial plains	15549.7	13618.5	8689.157	0	0	Least concern	Endangered
12.2.12	Closed heath on seasonally waterlogged sand plains	14153.52	10244.08	9617.492	0	0	Of concern	Endangered
10.7.4	Eucalyptus persistens low open woodland on pediments below scarps	13620.36	13199.4	6234.193	3.250009	0.023861	Least concern	Of Concern
12.3.14	Banksia aemula low woodland on alluvial plains usually near coast	13272.14	6713.683	5569.477	0	0	Of concern	Endangered
12.8.1	Eucalyptus campanulata tall open forest on Cainozoic igneous rocks	12983.61	10657.27	272.6104	0	0	Least concern	Of concern
12.5.9	Sedgeland to heathland in low lying areas on complex of remnant Tertiary surface and Tertiary sedimentary rocks	12845.53	7060.931	6965.318	0	0	Of concern	Endangered
6.3.8	Eucalyptus largiflorens +/- Acacia cambagei woodland on alluvium	12484.42	11306.75	10860.74	21.83401	0.17489	Least concern	Endangered
12.3.17	Simple notophyll fringing forest usually dominated by Waterhousea floribunda	11981.16	4050.29	2175.598	0	0	Of concern	Endangered
8.5.3	Eucalyptus drepanophylla +/- Corymbia clarksoniana, +/- E. platyphylla +/- C. dallachiana +/-	11957.08	6118.569	2655.585	0	0	Of concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	Melaleuca viridiflora woodland on broad low rises and gently sloping Tertiary sand plains							
2.3.18	Atalaya hemiglauca, Grevillea striata, Vachellia sutherlandii and Eucalyptus microtheca in mixed low woodlands on active Quaternary alluvial plains	11667.34	11496.68	0	1627.556	13.94967	Least concern	Of Concern
8.1.2	Samphire open forbland on saltpans and plains adjacent to mangroves	11572.96	10818.81	3301.187	0	0	Least concern	Of Concern
5.7.9	Aristida spp., Eriachne pulchella open tussock grassland wooded with Eucalyptus spp. +/- Acacia sibirica on undulating tops of dissected tablelands and ranges	10773.59	10715.35	0	1108.834	10.29215	Least concern	Of Concern
3.2.13	Semi-deciduous notophyll vine forest on beach ridges on the east coast	10457.83	10451.38	0	0	0	Least concern	Of concern
10.7.13	Ephemeral sparse tussock grassland ground below scarps	10207.98	10029.34	455.7895	35.50134	0.34778	Least concern	Of Concern
2.3.32	Aristida spp., Eriachne glauca tussock grassland in depressions and valley bottoms in the Donors Plateau subregion	10194.21	10185.75	0	570.2784	5.594137	Least concern	Of Concern
12.9-10.1	Tall open forest often with Eucalyptus resinifera, E. grandis, E. robusta, Corymbia intermedia on sedimentary rocks. Coastal	10088.26	4695.434	4453.932	0	0	Of concern	Endangered
11.3.13	Grevillea striata open woodland on coastal alluvial plains	8480.817	3143.128	2209.945	0	0	Of concern	Endangered
12.5.5	Eucalyptus portuensis, Corymbia intermedia open forest on remnant Tertiary surfaces. Usually deep red soils	7399.89	4972.132	2744.871	0	0	Of concern	Endangered
13.3.5	Eucalyptus camaldulensis fringing open forest	7371.811	4628.988	3193.839	0	0	Of concern	Endangered
11.5.18	Micromyrtus capricornia shrubland on Cainozoic sand plains and/or remnant surfaces	6653.693	3729.86	2109.302	0	0	Of concern	Endangered
7.1.2	Sporobolus virginicus grassland, samphire open forbland to sparse	6482.963	4858.063	3915.676	0	0	Of concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	forbland and bare saltpans on plains adjacent to mangroves							
12.1.1	Casuarina glauca woodland on margins of marine clay plains	6011.25	3761.81	2985.126	0	0	Of concern	Endangered
8.5.5	Eucalyptus exserta and/or Corymbia clarksoniana and/or E. crebra and/or Melaleuca spp. woodland on Tertiary sand plains	5485.267	2380.202	2174.718	0	0	Of concern	Endangered
11.3.33	Eremophila mitchellii open woodland on alluvial plains	4545.045	1940.23	879.5438	0	0	Of concern	Endangered
7.8.8	Eucalyptus tereticornis, E. reducta +/- Angophora floribunda open forest to woodland on basalt	4474.533	1528.307	0	0	0	Of concern	Endangered
11.5.14	Triodia sp. grassland with emergent trees on Cainozoic sand plains and/or remnant surfaces. Highly alkaline soils	4359.478	4226.185	4080.392	0	0	Of concern	Endangered
11.5.6	Triodia spp. grassland on Cainozoic sand plains and/or remnant surfaces	3309.911	2787.27	2787.27	0	0	Of concern	Endangered
11.1.3	Sedgelands on marine clay plains	2777.75	2976.682	2635.758	0	0	Of concern	Endangered
12.9-10.29	Eucalyptus cloeziana +/- E. propinqua, E. acmenoides, E. microcorys and E. grandis tall open forest on sedimentary rocks	2547.247	1269.787	523.4351	0	0	Of concern	Endangered
12.9-10.22	Closed sedgeland/shrubland on sedimentary rocks. Generally coastal	2148.895	1405.498	1306.841	0	0	Of concern	Endangered
10.5.9	Eucalyptus quadricostata open woodland on sandy plateaus	2137.758	2133.869	1592.394	0	0	Of concern	Endangered
7.3.29	Sedgelands and grasslands of permanently and semi-permanently inundated swamps, including areas of open water	2076.017	866.0819	678.5456	0	0	Of concern	Endangered
10.4.2	Acacia harpophylla low woodland on Cainozoic lake beds (subregion 3)	2040.207	1123.457	621.2804	0	0	Of concern	Endangered
11.3.23	Eucalyptus conica, E. nobilis, E. tereticornis, Angophora floribunda woodland on alluvial plains. Basalt derived soils	2002.049	684.1992	43.34305	0	0	Of concern	Endangered
11.3.40	Semi-deciduous notophyll to mesophyll vine forest, fringing or in the	511.1497	198.1282	177.7307	0	0	Of concern	Endangered

RE_Preclear	Desc	Total_Area Preclear	RemanntArea_ 2018	PotentialArea _remean	AreaProtected	Percent Protected	CurrentVM	New VM
	vicinity of watercourses, on lowlands (subregion 1).							
7.3.50	Melaleuca fluviatilis +/- vine forest species open forest to closed forest on alluvium fringing streams	491.5781	456.84	384.2566	0	0	Of concern	Endangered
12.9-10.26	Eucalyptus baileyana and/or E. planchoniana and/or E. psammitica woodland to open forest on quartzose sandstone	474.337	241.851	126.8573	0	0	Of concern	Endangered
11.8.9	Callitris spp. +/- vine thicket woodland on Cainozoic igneous rocks	452.7768	220.4293	140.6854	0	0	Of concern	Endangered
12.2.13	Open or dry heath on dunes and beaches	418.5627	360.9291	349.2728	0	0	Of concern	Endangered
12.11.26	Eucalyptus baileyana and/or E. planchoniana woodland to open forest on metamorphics +/- interbedded volcanics	369.7882	177.4412	160.5319	0	0	Of concern	Endangered
7.1.5	Melaleuca viridiflora or Melaleuca spp. +/- Acacia spp. +/- mangrove spp. woodland on plains adjacent to mangroves	328.5593	342.5395	261.4052	0	0	Of concern	Endangered
10.4.9	Corymbia spp. open woodland on Cainozoic lake beds	325.9871	275.7791	231.9059	0	0	Of concern	Endangered
6.12.1	Scattered Acacia aneura around granite boulders	263.8466	263.8466	244.8599	0	0	Of concern	Endangered
12.11.28	Eucalyptus helidonica, Angophora woodsiana, Corymbia gummifera woodland with a heathy shrub layer dominated by Leptospermum polygalifolium, Xanthorrhoea johnsonii and Banksia spinulosa var. collina on metamorphics +/- interbedded volcanics	115.051	62.6264	56.79899	0	0	Of concern	Endangered
12.9-10.9	Shrubland/low woodland on sandstone lithosols	79.55272	79.55272	72.69363	0	0	Of concern	Endangered
12.9-10.10	Melaleuca nodosa low open forest on sedimentary rocks	12.11124	1.13231	0.241184	0	0	Of concern	Endangered

5.7 Regional ecosystems likely to change status in the moderate scenario

Table A5-2: Regional ecosystems (RE_ID) likely to change status in the moderate scenario (*ie* if all probability values above the upper quartile are considered "high" (moderate)). In this table, we present the short description of the ecosystem as per the regional ecosystem description database ((Queensland Herbarium 2019)), the regional ecosystem's estimated historic extent (Total_Area_preclear), it's current extent (RemnantArea_2018), the extent to which the regional ecosystem overlaps with areas with potential for clearing (PotentialArea_remoderate), the percent of the regional ecosystem currently in protected areas, its current vegetation management status, and its predicted vegetation management status.

RE_ID	*Brief description*	*Total_Area Preclear*	*RemnantArea _2018*	*PotentialArea_ moderate*	*Percent_ protected*	*VM_ordered*	*New_VM*
6.5.7	Acacia aneura, Eucalyptus populnea +/- E. intertexta low woodland on run-on areas	842845.6	490925.9	234149.5	0	Least concern	Of Concern
11.5.1	Eucalyptus crebra and/or E. populnea, Callitris glaucophylla, Angophora leiocarpa, Allocasuarina luehmannii woodland on Cainozoic sand plains and/or remnant surfaces	790401.9	488053.1	426508.9	0	Least concern	Endangered
6.5.1	Acacia aneura, Eucalyptus populnea, E. melanophloia open forest on undulating lowlands	741722.9	262086.9	212658.8	0	Least concern	Endangered
6.5.3	Eucalyptus populnea, Acacia aneura +/- Eremophila mitchellii woodland within A. aneura communities	638037	190880.3	150163.2	0	Of concern	Endangered
6.5.2	Eucalyptus populnea, Acacia aneura and/or E. melanophloia woodland on Quaternary sediments	603681.8	192466.9	165378.9	0	Of concern	Endangered
11.5.13	Eucalyptus populnea +/- Acacia aneura +/- E. melanophloia woodland on Cainozoic sand plains and/or remnant surfaces	580371.9	95484.09	84192.39	2.74	Of concern	Endangered
11.10.11	Eucalyptus populnea, E. melanophloia +/- Callitris glaucophylla woodland on coarse-grained sedimentary rocks	549499.9	326779.1	201195.5	0	Least concern	Of Concern
11.9.10	Eucalyptus populnea open forest with a secondary tree layer of Acacia harpophylla and sometimes Casuarina cristata on fine-grained sedimentary rocks	492353.5	78481.34	41071.59	0	Of concern	Endangered
11.3.28	Eucalyptus coolabah +/- Casuarina cristata open woodland on alluvial plains	470048.9	60483.49	45192.56	0	Of concern	Endangered
6.3.7	Eucalyptus coolabah, Acacia stenophylla low open woodland on alluvium	402469.1	379511.1	325761.8	0	Least concern	Of Concern
11.5.5	Eucalyptus melanophloia, Callitris glaucophylla woodland on Cainozoic sand plains and/or remnant surfaces. Deep red sands	391314.6	135353.8	68060.83	0	Least concern	Of Concern

6.3.18	Eucalyptus populnea +/- Eremophila mitchellii +/- Acacia aneura +/- Eucalyptus melanophloia woodland on flat alluvial plains	360479.7	191290	123373.1	0	Least concern	Of Concern
11.7.4	Eucalyptus decorticans and/or Eucalyptus spp., Corymbia spp., Acacia spp., Lysicarpus angustifolius woodland on Cainozoic lateritic duricrust	356834.9	230814.5	151636.7	0	Least concern	Of Concern
6.3.15	Astrebla lappacea, A. pectinata +/- A. elymoides grassland on alluvium	329342.2	323534.2	280005.3	0	Least concern	Of Concern
6.4.3	Eucalyptus populnea, Casuarina cristata or Acacia harpophylla +/- Geijera parviflora woodland on clay plains	305948.9	39133.87	36507.37	0	Of concern	Endangered
6.5.13	Acacia aneura +/- Eucalyptus populnea +/- E. melanophloia +/- Brachychiton populneus low woodland on sand plains	298623	134745.1	91120.94	0	Least concern	Endangered
11.9.11	Acacia harpophylla shrubland on fine-grained sedimentary rocks	287465.4	53264.11	23411.81	0	Of concern	Endangered
6.5.17	Eucalyptus populnea +/- E. melanophloia +/- Callitris glaucophylla +/- Acacia aneura woodland on sand plains	275420.1	72688.03	71910.89	0	Of concern	Endangered
11.9.3	Dichanthium spp., Astrebla spp. grassland on fine-grained sedimentary rocks	272178.6	154083.6	81451.32	0	Least concern	Of Concern
11.3.17	Eucalyptus populnea woodland with Acacia harpophylla and/or Casuarina cristata on alluvial plains	263856.9	33972.8	24857	0	Of concern	Endangered
6.5.5	Eucalyptus populnea +/- E. intertexta +/- Acacia aneura +/- Callitris glaucophylla woodland on Quaternary sediments	252083.4	59279.96	59116.27	0	Of concern	Endangered
6.3.21	Acacia aneura, A. excelsa and/or Geijera parviflora low woodland on low alluvial sand dunes	246415.9	221855	141529.3	0	Least concern	Of Concern
11.3.19	Callitris glaucophylla, Corymbia spp. and/or Eucalyptus melanophloia open forest to woodland on Cainozoic alluvial plains	240955.5	92294.02	65855.43	0	Least concern	Of concern
6.5.9	Acacia aneura, Eucalyptus populnea +/- E. melanophloia shrubby low woodland on Quaternary sediments	236089.8	79584.12	34707.65	0	Least concern	Of Concern
11.5.20	Eucalyptus moluccana and/or E. microcarpa and/or E. woollsiana +/- E. crebra woodland on Cainozoic sand plains	233802.5	153060	102805.9	0	Least concern	Of Concern
11.7.1	Acacia harpophylla and/or Casuarina cristata and Eucalyptus thozetiana or E. microcarpa woodland on lower scarp slopes on Cainozoic lateritic duricrust	203796.7	79026.51	23073.59	0	Least concern	Of Concern

11.7.7	Eucalyptus fibrosa subsp. nubilis +/- Corymbia spp. +/- Eucalyptus spp. woodland on Cainozoic lateritic duricrust	203764.3	174902.9	143560.3	0	Least concern	Of Concern
11.3.5	Acacia cambagei woodland on alluvial plains	165769.9	52025.17	17075.2	0	Least concern	Of Concern
10.3.27	Eucalyptus populnea woodland to open woodland on alluvial plains	160270.3	65073.38	31529.96	0	Least concern	Of Concern
11.5.4	Eucalyptus chloroclada, Callitris glaucophylla, C. endlicheri, Angophora leiocarpa woodland on Cainozoic sand plains and/or remnant surfaces	145393.4	110958.5	98304.84	0	Least concern	Endangered
11.3.18	Eucalyptus populnea, Callitris glaucophylla, Allocasuarina luehmannii shrubby woodland on alluvium	143025.1	80015.41	50212.98	1.09	Least concern	Of Concern
6.5.11	Acacia aneura +/- Eucalyptus populnea low woodland on sand plains	136763.7	67670.37	27176.14	0	Least concern	Of Concern
6.3.14	Astrebla spp., Dichanthium spp. open grassland on alluvium	131054.4	125112.2	92757.07	0	Least concern	Of Concern
10.4.8	Astrebla squarrosa and Iseilema vaginiflorum +/- Dichanthium sericeum and Panicum laevinode open tussock grassland on Cainozoic lake beds	127995.6	119610.5	92868.18	10.14	Least concern	Of Concern
11.3.26	Eucalyptus moluccana or E. microcarpa woodland to open forest on margins of alluvial plains	124114.6	45279.71	11996.51	0	Least concern	Of Concern
11.3.14	Eucalyptus spp., Angophora spp., Callitris spp. woodland on alluvial plains	107991.8	82586.37	78211.54	1.24	Least concern	Endangered
6.3.17	Callitris glaucophylla, Corymbia tessellaris, Acacia excelsa +/- C. clarksoniana open woodland on old alluvial dunes and sand plains	106222.7	46031.55	36086.57	0	Least concern	Endangered
10.9.6	Acacia cambagei low woodland to open woodland on Cretaceous sediments	105425.3	37067.62	7350.433	1.30	Least concern	Of Concern
6.3.16	Callitris glaucophylla, Acacia excelsa, Geijera parviflora +/- Acacia aneura woodland on alluvial dunes	97871.66	85259.75	53395.93	0	Least concern	Of Concern
11.3.15	Eucalyptus coolabah, Acacia stenophylla, Duma florulenta fringing open woodland on alluvial plains	90938.08	24024.43	22021.73	0	Of concern	Endangered
6.3.25	Acacia harpophylla and/or A. cambagei low woodland to woodland on alluvial plains	87234.22	59882.28	54566.17	0	Least concern	Endangered
6.7.5	Eucalyptus thozetiana or E. cambageana, Acacia harpophylla woodland on scarps	78804.53	33840.2	10847.14	0	Least concern	Of Concern
6.3.24	Eucalyptus coolabah or E. populnea woodland on alluvial plains	78110.77	29528.99	28160.43	0.00000	Least concern	Endangered
11.5.21	Corymbia bloxsomei +/- Callitris glaucophylla +/- Eucalyptus crebra +/- Angophora leiocarpa woodland on Cainozoic sand plains and/or remnant surfaces	78079.85	73112.36	68572.92	0.20	Least concern	Endangered

11.7.5	Shrubland on natural scalds on deeply weathered coarse-grained sedimentary rocks	75678.45	64501.77	43962.22	0	Least concern	Of Concern
11.4.4	Dichanthium spp., Astrebla spp. grassland on Cainozoic clay plains	67801.27	24703.47	10460.77	0	Least concern	Of Concern
11.3.6	Eucalyptus melanophloia woodland on alluvial plains	65355.02	28947.18	7577.377	0	Least concern	Of Concern
6.3.1	Eucalyptus camaldulensis woodland on alluvium within Acacia aneura associations	61781.06	46588.11	28722.5	0	Least concern	Of Concern
10.3.3	Acacia harpophylla and/or Eucalyptus cambageana low open woodland to open woodland on alluvial plains	60733.17	24980.78	6977.093	0	Least concern	Of Concern
12.5.12	Eucalyptus racemosa subsp. racemosa, E. latisinensis +/- Corymbia gummifera, C. intermedia, E. bancroftii woodland with heathy understorey on remnant Tertiary surfaces	58022.07	16353.33	7064.477	0	Of concern	Endangered
11.3.37	Eucalyptus coolabah fringing woodland on alluvial plains	53028	30374.92	14711.08	0	Least concern	Of Concern
11.3.20	Forb and/or grassland +/- scattered Atalaya hemiglauca, Flindersia maculosa, Acacia spp. on alluvial plains	47985.81	25866.52	20418.18	0	Least concern	Endangered
12.3.5	Melaleuca quinquenervia open forest on coastal alluvium	46279.94	20594.94	11808.96	0	Least concern	Endangered
6.5.6	Acacia aneura, Eucalyptus populnea low woodland on run-on plains	45836.24	28774.84	12918.27	0	Least concern	Of Concern
6.5.19	Callitris glaucophylla +/- Angophora melanoxylon +/- Eucalyptus melanophloia +/- E. chloroclada open woodland on Cainozoic sediments derived from old alluvial levees and dunes	43090.57	19400.27	19338.8	0	Least concern	Endangered
7.3.8	Melaleuca viridiflora +/- Eucalyptus spp. +/- Lophostemon suaveolens open forest to open woodland on poorly drained alluvial plains	39109.94	15088.66	5320.652	0	Least concern	Endangered
11.3.16	Eucalyptus largiflorens +/- Acacia cambagei +/- A. harpophylla woodland to low open woodland on alluvial plains	37005.59	14382.41	13711.05	1.83	Least concern	Endangered
6.3.12	Acacia omalophylla +/- A. microsperma +/- Eucalyptus coolabah tall open shrubland on alluvium	36825.64	31620.91	22254.63	0	Least concern	Endangered
11.9.8	Macropteranthes leichhardtii thicket on fine grained sedimentary rocks	36062.68	11957.67	1278.694	0	Least concern	Of Concern
7.3.45	Corymbia clarksoniana +/- C. tessellaris +/- E. drepanophylla open forest to open woodland on alluvial plains	33577.2	11414.49	3319.825	0	Least concern	Endangered

12.3.6	Melaleuca quinquenervia +/- Eucalyptus tereticornis, Lophostemon suaveolens, Corymbia intermedia open forest on coastal alluvial plains	33157	12988.93	4241.204	0	Least concern	Endangered
12.2.7	Melaleuca quinquenervia or rarely M. dealbata open forest on sand plains	32159.52	19240.61	10393.9	0	Least concern	Endangered
12.9-10.14	Eucalyptus pilularis tall open forest on sedimentary rocks	30196.82	13288.32	3638.761	0	Least concern	Of Concern
6.7.2	Acacia microsperma open forest on upper and footslopes	28819.76	11586.24	7871.707	0	Least concern	Endangered
12.3.13	Closed heathland on seasonally waterlogged alluvial plains usually near coast	22539.78	13891.79	7824.27	2.24	Least concern	Endangered
12.3.2	Eucalyptus grandis tall open forest on alluvial plains	22412.47	7639.122	3422.7	0	Of concern	Endangered
11.9.14	Lysiphyllum carronii, Atalaya hemiglauca +/- Eucalyptus melanophloia +/- Acacia excelsa open woodland	21473.54	8506.139	5766.892	5.081	Of concern	Endangered
13.11.5	Eucalyptus sideroxylon, E. fibrosa subsp. nubilis open forest on metamorphics	19982.83	11242.81	3228.462	0	Least concern	Of Concern
12.3.4	Melaleuca quinquenervia, Eucalyptus robusta woodland on coastal alluvium	18083.71	8390.266	6427.134	0	Of concern	Endangered
12.2.5	Corymbia intermedia +/- Lophostemon confertus +/- Banksia spp. +/- Callitris columellaris open forest on beach ridges usually in southern half of bioregion	16405.25	10966.06	5247.627	0	Least concern	Of Concern
6.3.10	Tecticornia spp. open succulent shrubland on alluvium	16118.26	16118.26	10674.24	0	Least concern	Of Concern
10.3.7	Astrebla spp., Iseilema vaginiflorum and/or Dichanthium fecundum or Bothriochloa ewartiana tussock grassland on alluvial plains	15549.7	13618.5	6328.173	0	Least concern	Of Concern
12.2.12	Closed heath on seasonally waterlogged sand plains	14153.52	10244.08	7954.904	0	Of concern	Endangered
10.7.4	Eucalyptus persistens low open woodland on pediments below scarps	13620.36	13199.4	4730.735	0	Least concern	Of Concern
12.3.14	Banksia aemula low woodland on alluvial plains usually near coast	13272.14	6713.683	3821.657	0	Of concern	Endangered
12.5.9	Sedgeland to heathland in low lying areas on complex of remnant Tertiary surface and Tertiary sedimentary rocks	12845.53	7060.931	3382.231	0	Of concern	Endangered
6.3.8	Eucalyptus largiflorens +/- Acacia cambagei woodland on alluvium	12484.42	11306.75	7774.596	0	Least concern	Endangered
8.1.2	Samphire open forbland on saltpans and plains adjacent to mangroves	11572.96	10818.81	913.0905	0	Least concern	Of Concern
10.7.13	Ephemeral sparse tussock grassland ground below scarps	10207.98	10029.34	229.7919	0	Least concern	Of Concern

12.9-10.1	Tall open forest often with Eucalyptus resinifera, E. grandis, E. robusta, Corymbia intermedia on sedimentary rocks. Coastal	10088.26	4695.434	3676.024	0	Of concern	Endangered
12.1.1	Casuarina glauca woodland on margins of marine clay plains	6011.25	3761.81	2169.115	0	Of concern	Endangered
8.5.5	Eucalyptus exserta and/or Corymbia clarksoniana and/or E. crebra and/or Melaleuca spp. woodland on Tertiary sand plains	5485.267	2380.202	1168.362	0	Of concern	Endangered
11.5.6	Triodia spp. grassland on Cainozoic sand plains and/or remnant surfaces	3309.911	2787.27	2303.072	0	Of concern	Endangered
10.4.2	Acacia harpophylla low woodland on Cainozoic lake beds (subregion 3)	2040.207	1123.457	550.002	0	Of concern	Endangered
12.2.13	Open or dry heath on dunes and beaches	418.5627	360.9291	291.4716	0	Of concern	Endangered
12.11.26	Eucalyptus baileyana and/or E. planchoniana woodland to open forest on metamorphics +/- interbedded volcanics	369.7882	177.4412	126.067	0.010741016	Of concern	Endangered
6.12.1	Scattered Acacia aneura around granite boulders	263.8466	263.8466	208.7228	0	Of concern	Endangered
6.3.23	Springs on recent alluvia, ancient alluvia and fine-grained sedimentary rock	130.4185	119.3061	54.16155	0	Endangered	Of Concern
12.9-10.10	Melaleuca nodosa low open forest on sedimentary rocks	12.11124	1.13231	0	0	Of concern	Endangered

5.8 Regional ecosystems likely to change status in the unlikely scenario

Table A5-3 Regional ecosystems likely to change status in the unlikely scenario (*ie* if all probability values above the lower whisker are considered "high" (likely)). In this table, I present the short description of the ecosystem as per the regional ecosystem description database (), the regional ecosystem's estimated historic extent (Total_Area_preclear), its current extent (RemnantArea_2018), the extent to which the regional ecosystem overlaps with areas which have the potential for clearing (PotentialArea_relower), the per cent of the regional ecosystem currently in protected areas, its current vegetation management status, and its predicted vegetation management status.

RE_code	*Desc*	*Total_Area_ preclear*	*RemnantArea_ 2018*	*PotentialArea_ Likely*	*Pct_pas*	*VM_current*	*VM_new*
11.3.5	Acacia cambagei woodland on alluvial plains	165769.941	52025.16636	3441.257348	0	Least concern	Of concern
6.5.11	Acacia aneura +/- Eucalyptus populnea low woodland on sand plains	136763.6783	67670.36834	27176.13742	0	Least concern	Of concern
6.7.5	Eucalyptus thozetiana or E. cambageana, Acacia harpophylla woodland on scarps	78804.52769	33840.19617	10847.14121	0	Least concern	Of concern
6.3.24	Eucalyptus coolabah or E. populnea woodland on alluvial plains	78110.77242	29528.98643	492.893495	0	Least concern	Of concern
12.5.12	Eucalyptus racemosa subsp. racemosa, E. latisinensis +/- Corymbia gummifera, C. intermedia, E. bancroftii woodland with heathy understorey on remnant Tertiary surfaces	58022.072	16353.33017	7064.476989	0	Of concern	Endangered
6.5.6	Acacia aneura, Eucalyptus populnea low woodland on run-on plains	45836.24438	28774.84439	12918.26992	0	Least concern	Of concern
11.3.16	Eucalyptus largiflorens +/- Acacia cambagei +/- A. harpophylla woodland to low open woodland on alluvial plains	37005.59391	14382.41143	3848.493817	1.832445	Least concern	Of concern
12.3.6	Melaleuca quinquenervia +/- Eucalyptus tereticornis, Lophostemon suaveolens, Corymbia intermedia open forest on coastal alluvial plains	33156.99926	12988.93342	4241.204323	0	Least concern	Endangered
12.9-10.14	Eucalyptus pilularis tall open forest on sedimentary rocks	30196.82347	13288.3174	3638.760587	0	Least concern	Of concern
12.3.13	Closed heathland on seasonally waterlogged alluvial plains usually near coast	22539.78096	13891.78564	7824.270272	2.240245	Least concern	Endangered
12.3.2	Eucalyptus grandis tall open forest on alluvial plains	22412.47465	7639.122112	3422.700231	0	Of concern	Endangered

RE_code	Desc	Total_Area_ preclear	RemnantArea_ 2018	PotentialArea_ Likely	Pct_pas	VM_current	VM_new
12.3.4	Melaleuca quinquenervia, Eucalyptus robusta woodland on coastal alluvium	18083.70657	8390.266227	6427.13439	0	Of concern	Endangered
12.2.5	Corymbia intermedia +/- Lophostemon confertus +/- Banksia spp. +/- Callitris columellaris open forest on beach ridges usually in southern half of bioregion	16405.24767	10966.06198	5247.626676	0	Least concern	Of concern
6.3.10	Tecticornia spp. open succulent shrubland on alluvium	16118.25933	16118.2593	10674.24273	0	Least concern	Of concern
12.3.14	Banksia aemula low woodland on alluvial plains usually near coast	13272.14298	6713.682702	3821.656875	0	Of concern	Endangered
12.5.9	Sedgeland to heathland in low lying areas on complex of remnant Tertiary surface and Tertiary sedimentary rocks	12845.532	7060.93124	3382.23071	0	Of concern	Endangered
2.3.18	Atalaya hemiglauca, Grevillea striata, Vachellia sutherlandii and Eucalyptus microtheca in mixed low woodlands on active Quaternary alluvial plains	11667.34162	11496.67659	0	0	Least concern	Of concern
8.1.2	Samphire open forbland on saltpans and plains adjacent to mangroves	11572.95579	10818.80661	913.0905199	0	Least concern	Of concern
12.12.4	Eucalyptus acmenoides +/- Syncarpia glomulifera woodland on Mesozoic to Proterozoic igneous rocks, especially granite	11041.93058	10427.16815	0	0	Least concern	Of concern
9.12.31	Eucalyptus leptophleba, Corymbia clarksoniana and E. crebra +/- C. dallachiana woodland on igneous rocks	10982.42695	10437.16347	5.252439858	0	Least concern	Of concern
3.2.13	Semi-deciduous notophyll vine forest on beach ridges on the east coast	10457.82719	10451.38305	0	0	Least concern	Of concern
1.9.1	Astrebla spp. grassland on shallow clays on limestones	10288.05705	10267.44549	0	0	Least concern	Of concern
8.5.5	Eucalyptus exserta and/or Corymbia clarksoniana and/or E. crebra and/or Melaleuca spp. woodland on Tertiary sand plains	5485.267115	2380.201995	1168.362128	0	Of concern	Endangered
6.12.1	Scattered Acacia aneura around granite boulders	263.8466085	263.8466135	208.7227979	0	Of concern	Endangered
12.9-10.10	Melaleuca nodosa low open forest on sedimentary rocks	12.11124268	1.132310152	0	0	Of concern	Endangered

END