Mapping Changes in Landscape-Scale Patterns of Vegetation in Coal Seam Gas Development Areas

Final Dissertation

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Abstract

In the 15 years to 2013, the rate of coal seam gas (CSG) development in Queensland increased dramatically. Drilling of gas wells and installation of associated infrastructure sometimes requires the removal of vegetation. Although a change in vegetation cover on a small scale does not necessarily correspond to significant landscape-scale change, research overseas indicates that the extent and configuration of vegetation patches in a landscape is altered in areas of concentrated oil and gas extraction. The focus of previous research has been on oil and shale gas activity, mainly in North America. There has been little work on the nature and extent of the impact of similar developments in an Australian context, or impacts due specifically to CSG activity anywhere in the world.

The aim of this study is to determine the nature of land cover change in a region of southern Queensland under intense CSG development. The extent and fragmentation of vegetation in 1999, immediately before CSG development began, is compared to the extent and fragmentation of vegetation in 2013, after 1562 coal seam gas wells had been drilled. Land cover was determined by classification of a LANDSAT 4 image taken in 1999 and a Landsat 8 image taken in 2013. ArcGIS 10.2 was used for image manipulation, and vegetation patch metrics were determined using FRAGSTATS 4.2 software. For comparison, the same metrics were also calculated in hot spot regions defined in two different ways to focus more closely around drilling sites. Similarly, the same metrics were calculated on a classified image modified to ensure that known linear clearings were continuously defined despite the automatic classification.

The study finds that processes causing land cover change in the study area generally have a net positive effect on the landscape. Positive changes were observed despite clear evidence that CSG activity has directly led to vegetation loss on a small scale around CSG developments within the study area. This study shows that, while CSG development has a distinguishable impact on land cover at a landscape scale in southern Queensland, other more significant drivers of change mask the effect of CSG activity.

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1 Introduction

1.1 Introduction

Gas production is a prominent industry in Queensland. While almost 30% of Australia's CSG reserves are found in the Bowen and Surat basins of southern Queensland, the industry has not developed until recently (Australian Energy Regulator 2013). However, the rate of CSG development in Queensland during the decade-and-a-half to 2013 was very high. Currently 22.5% of CSG production for the domestic market occurs in the Bowen and Surat basins (Australian Energy Regulator 2013; QLD Department of Natural Resources and Mines January 2014). CSG and conventional gas produced in Queensland is sold exclusively to the domestic market, including for production of electricity. Exports of gas are expected to begin in 2014, with subsequent increasing capacity for export (Australian Energy Regulator 2013). Development of CSG in the Surat basin will be a major contributor to the supply of gas for export through the Queensland Curtis Liquid Natural Gas project (QGC Limited 2009b).

Due to increasing demand for gas, large areas in southern and central Queensland are subject to the small intense disturbances, densely distributed across the landscape, which are typical of gas extraction activity. Clearing of natural land cover, or conversion of agricultural land, is necessary for the construction of well pads and associated infrastructure. The effects on land cover extent and structure caused by activities and infrastructure required for gas extraction may be determined by analysing remote sensing data. The approach in this work is to complete a longitudinal study on a landscape scale using satellite observation and publically available government datasets. The study indicates the cumulative effects of all aspects of the industry on vegetation extent and distribution.

1.2 The Organisation of the Report

The report is broken into six major chapters: an introduction to the topic, review of literature, description of methods, results, discussion and conclusion. The introductory chapter provides:

- A background to the topic, including a statement of the problem,
- A description of the significance of the study,
- The objects of the study,
- A definition of the project scope, and consequently, the limitations on the conclusions drawn from the study.

In Chapter 2, significant literature on the topic is reviewed, creating a nest for this study. Literature on disturbance due to oil and gas extracting activity, methods of assessing land cover extent and configuration and the importance of edge and barrier effects are considered in the literature review. Chapter 3 provides a description of methods employed including an introduction of the specific study area, a justification of the chosen methods of data analysis and an outline of the resources. Chapter 4 outlines the results of the project, leading into a discussion and analysis of the results in Chapter 5. Conclusions are drawn in Chapter 6.

1.3 Statement of the Problem

Land cover patch extent and configuration is potentially altered in areas of concentrated CSG extraction. The impact is a consequence of the direct footprint of CSG infrastructure as well as indirect impacts of disturbance to surrounding land users. However, the nature and extent of this impact, especially in an Australian environment, is not well understood. The impact in Australia may be unique due to differences in regulation, technical requirements for CSG, response of the landscape to disturbance and composition of the landscape. While oil and gas developments are studied in other countries, consideration of the impact on land cover change and fragmentation due to CSG is limited. LANDSAT 4 images taken in 1999, during the earliest developments of the industry in Australia, and Landsat 8 images taken in 2013, provide evidence of the scale of surface disturbances caused by CSG extraction. They may indicate the potential impacts of further development of the industry on the environment.

1.4 Significance of the Study

CSG developments are a recent and controversial addition to the energy production industry in Australia and the expansion of the industry has become a divisive issue in Australian society. However, there is limited evidence in the public domain, particularly academic literature, to support claims made by proponents and opponents of CSG extraction. This is true in Australia as well as in countries where the industry is well developed such as the USA and Canada. There is, however, very strong evidence in the literature that vegetation loss and fragmentation are major contributors to loss of biodiversity and reduced ecosystem health (Murcia 1995; Wilson, Neldner & Accad 2002). This study will provide a characterisation of landscape-scale change occurring in a region of Australia under heavy CSG development. It will provide an increased understanding and awareness of the true scale of the impact of gas extraction industries, and allow for better planning of future developments in Queensland and other parts of Australia.

1.5 Objectives

The objectives of this work were to:

1. Quantify the land cover change occurring in Queensland, on a landscape scale, in regions of concentrated CSG development.
2. Determine changes to the degree of fragmentation of remnant native vegetation stands in a region of concentrated CSG development.

3. Make comment on the probable relative effect of CSG activity on land cover and vegetation fragmentation change.

1.6 Scope and Limitations

There are a number of important principles that guide the design of this study. It was intended that:

- The study would only analyse the effects of CSG extraction on land cover change and fragmentation. Other environmental impacts of the industry were not considered, and the broader merits and drawbacks of the CSG industry were not analysed in the context of current stakeholder policies.
- The analysis is intended to draw general conclusions about the nature of change in the study area. Under the broad approach, the study is able to demonstrate the plausibility of impacts to different actors in the environment. A more focused analysis would be required to determine the impacts of change on particular species or ecological groups.
- The study focused on a binary classification of vegetated and non-vegetated areas. The vegetated areas can be further classified into vegetation sub-types. While it is unclear how fragmented individual types of vegetation were at the commencement of CSG development, a study such as that conducted by Finn and Knick (2011) could reconstruct a historical landscape as a baseline to analyse the impact on individual vegetation types. This analysis was ruled out of the scope of the current study, but is suggested as a possible future project.
- The study focused on the impact of CSG extraction, rather than other forms of oil and gas activity. The Bowen and Surat basins contain less than 1% of known conventional gas reserves and contribute less than 1% to conventional gas production for the domestic market (Australian Energy Regulator 2013). Most

conventional gas activity occurs around Roma and Surat, and in the far South-West of Queensland between Eromanga and Cameron's Corner (QLD Department of Natural Resources and Mines 2014c). Conventional gas activity in the study area was minimal, and occurred prior to 1999.

- Despite a focus on a 390,200-hectare region of Queensland, wider implications for the industry in Australia are drawn from the study. Similarly, the study compares two images taken 14 years apart, but the amount of change in this time scale is intended to be relevant at other time-scales.

There are limitations to the methods chosen to interpret the data collected in this study. Principally, it is recognised that:

- All data has been provided by external agencies. The data is considered to be reliable, but errors or misrepresentations could impact the validity of the results of this study.
- Classification of satellite imagery is guaranteed only to 80% accuracy. Some potential classification errors are identified in the discussion chapter.
- A generalisation algorithm is not used. Small, even single pixel, inaccuracies in classification may impact some metrics significantly, particularly those metrics that measure edge effects and core areas. These anomalies could be removed using a homogenisation technique. No such alteration was made to the data in order to preserve the impact of the small features characteristic of CSG activity on the classified image.
- The nature of raster images impacts on edge effect and shape metrics because of the stepped-nature of boundaries around cells diagonal to one another. In this case, the scale of all images was the same, so comparisons within the study could be made. However,

the results of the fragmentation analysis may only be directly compared to images in other studies that have a cell size of 30m.

- Analysis of landscape-wide change allows the cumulative effects of gas extraction activities to be analysed, but land cover change due to other activities also impact on the results of the study. Analysis of hotspot areas, containing more concentrated activity, is intended to filter out some of the unrelated activity. However, it is difficult to completely isolate the impacts of a single activity when the different activities are occurring in the same space and time. Some infrastructure is developed outside hotspot areas, and other activities impacting on land cover change continue to occur within hotpot regions.
- Narrow clearings for roads and pipelines are not well represented on the map. Tree branches may hide the full extent of a road in a satellite image. Further, the resolution of the images is 30m, in the same order of magnitude as the width of a clearing for linear infrastructure. Even single pixel discontinuities in linear clearing could have major effects on the measurement of landscape metrics. A method of forcing all cells through which roads ran to be classified as 'non-forested' cells, ensured that small linear clearings were well defined on the classified image. This transformation was successful but had the disadvantage of increasing the size of roads and removing road verge vegetation where the road raster did not align with an observed clearing exactly. The road verge vegetation is important in some parts of the study area, particularly where it exists as isolated patches.
- The analysis of edge effects required an assumption about the depth of the edge zone. In this study the edge zone was assumed to be 90m deep, in accordance with general practice in other similar studies. However, edge zones are difficult to define and may be different for individual species and in different parts of the world.

Despite the limitations of the study, useful conclusions are drawn from the data and analysis. The study raises important questions about our understanding of Australian landscapes under pressure from CSG development, and indicates the type of work we need to undertake in order to understand and manage it better.

2 Literature Review

2.1 Introduction

This chapter provides a review of literature relevant to the current study. In particular, the review considers the environmental impacts of CSG, land cover change during the last two centuries in the study area, methods of land cover change analysis, landscape ecology, and various means of measuring landscape fragmentation. This chapter seeks to demonstrate the maturity of the field of landscape ecology, and draw attention to concepts that are important in the analysis of the impacts of CSG. The review also considers software and analysis techniques developed for other landscape-scale investigations land cover change and fragmentation, and attempts to inform the choice of techniques in this study to improve the potential for cross-analysis between studies.

The review shows that, while the theory of land cover change and fragmentation is well developed, it has not been widely applied to landscapes impacted by oil and gas development. Of particular interest in the review are CSG developments, on which there has been no publically available research completed in Australia. Research on the more developed industry in North America is limited, and of unknown applicability in an Australian context. Some studies on similar industries such as shale gas, and conventional oil extraction are available in the academic literature. These studies are significant for comparison in a land-cover study, as all forms of gas extraction activities require relatively small but interconnected production sites scattered throughout a production basin.

2.2 Gas Extraction

Methane trapped in coal seams is increasingly being exploited to supplement Australia's conventional gas supplies. The gas is naturally stored within pores in the coal. Reducing the pressure inside the coal seams, by the removal of water, allows gas to flow to the surface through production wells (Hamawand, Yusaf & Hamawand 2013). In some cases, more gas may be retrieved from wells by physically and chemically increasing the porosity of the coal stratum. This is a process known as 'fracking' (Bradd et al. 2013). The gas contains a very high percentage of methane (~95%), which is used domestically or exported as Liquefied Natural Gas (LPG) (Hamawand, Yusaf & Hamawand 2013).

Primarily, CSG available for extraction occurs in large quantities in the Surat and Bowen Basins of Queensland with smaller quantities in the Gunnedah and Sydney Basins in New South Wales (Williams, Milligan & Stubbs 2013). CSG production occurs in a number of countries. At the turn of the millennium, CSG reserves were relatively undeveloped in Canada, though the industry in the USA was well established (Griffith & Severson-Baker 2003). Major investment in Australia's CSG industry began in the late 90s, and the industry in Australia has developed rapidly in the last 15 years. In 1999/2000, in Queensland, fewer than 50 wells were drilled annually, but the number has risen to more than 1300 wells annually in 2012/2013 (QLD Department of Natural Resources and Mines January 2014). In 2012/2013, coal seams in Queensland yielded 7057.68 Mm^3 of gas, with production solely from the Surat and Bowen Basins (QLD Department of Natural Resources and Mines January 2014).

While CSG is economically important, various environmental issues are attributed to CSG extraction. These include:

- Loss of vegetation (Finn & Knick 2011; Fisher 2001),
- Habitat fragmentation (Finn & Knick 2011; Griffith & Severson-Baker 2003),
- Disturbance by noise (Finn & Knick 2011; Fisher 2001; Griffith & Severson-Baker 2003),
- Emissions of dust (Fisher 2001),

- Emissions of greenhouse gasses (Fisher 2001; Griffith & Severson-Baker 2003; Hamawand, Yusaf & Hamawand 2013),
- Release of co-produced water containing toxic chemicals or a chemical composition different to surface and ground receiving waters (Finn & Knick 2011; Fisher 2001; Griffith & Severson-Baker 2003; Hamawand, Yusaf & Hamawand 2013; McBeth, Reddy & Skinner 2003),
- Depletion of aquifers (Finn & Knick 2011; Fisher 2001),
- Pollution of aquifers by methane (Fisher 2001),
- Cross-aquifer contamination (Bradd et al. 2013),
- Soil erosion (Finn & Knick 2011),
- Invasion by exotic species (Drohan et al. 2012; Finn & Knick 2011); and
- Creation of an environment friendly to disease vectors (particularly detention basins) (Finn & Knick 2011).

Each of these potential impacts must be monitored using unique approaches. All, but landscape fragmentation, are outside the scope of this project. This study will consider the effects of CSG on broad-scale surface vegetation patterns.

2.3 Historical Land Cover and Landscape Structure Change in the Study Area

This study will consider vegetation loss and fragmentation in a part of southern Queensland that forms part of the Brigalow Belt bioregion. The current study extends the work of Seabrook, McAlpine and Fensham (2007) into historical changes in the Brigalow Belt bioregion by partially using the same study area. Bioregions are broadly defined as an area of similar structural geology, climate, flora and fauna. The Brigalow Belt bioregion is one of the most extensively cleared bioregions in Queensland with 61% of vegetation in that region cleared since European settlement (Seabrook, McAlpine & Fensham 2006; Wilson, Neldner & Accad 2002). A number of the vegetation types are now considered to be under-represented in remnant native vegetation (Seabrook, McAlpine & Fensham 2006). Alluvial Open Eucalypt Woodland and Acacia Forest have been cleared to a greater extent than Dry Eucalypt Woodlands (Seabrook, McAlpine & Fensham 2006; Wilson, Neldner & Accad 2002).

Settlers initially assumed land in the Brigalow Belt in the mid-nineteenth century for pastoral purposes, which required minimal clearing of the landscape. Some forest was cleared for timber, and cropping was confined to small parts of the Darling Downs (Seabrook, McAlpine & Fensham 2006). Later, with the introduction of mechanised methods of clearing in the twentieth century, large areas of land throughout the Brigalow Belt could be converted to improved pastures, or cultivated land. Conversion to crops was considered ideal as regular ploughing prevented regrowth of Brigalow forest stands (Seabrook, McAlpine & Fensham 2006). Clearing was driven by social, political and economic factors, though the specific patterns of clearing are influenced by biophysical factors, particularly soil type (Seabrook, McAlpine & Fensham 2007).

Today, vegetation in this bioregion is heavily disturbed. It has been noted that much of the remnant vegetation, particularly Acacia Forest, is in highly undesirable shapes, such as narrow strips along fence lines (QGC Limited 2009a; Seabrook, McAlpine & Fensham 2007). Given its history of disturbance, further vegetation loss (measured in objective number one) and fragmentation (measured in objective number two) due to CSG activity could potentially be very significant. Further, to achieve objective number three, it is important to recognise the place of CSG in the context of other drivers of land cover change in the study area.

2.4 Land Cover Change

The quantification of land cover change is the focus of objective one of this study. Though, worldwide, land cover change has been analysed in a variety of landscapes, post CSG landscapes are not widely considered. Some published studies on oil development in North America are relevant to compare with the results of this work. In particular, the authors of a study in Wyoming between 1900 and 2009 note that they are amongst the only researchers to consider landscape-scale changes in land cover due to oil and gas activity (Finn & Knick 2011). They found that 8.3% of land cover within 0.2km of an oil well had been converted to road or well pad and 97% of the development was attributable to oil and gas development (Finn & Knick 2011). Given the small size of the hotspot area defined around each well (0.2km radius), such a finding is not surprising. However, landscape wide, 0.97% of land was converted, and 20% was estimated to be due to oil development (Finn & Knick 2011).

Studies on land cover change due to shale gas development produced similar results to those presented by Finn and Knick (2011). In a study of Marcellus shale gas extraction using a predictive model in Pennsylvania, less that 1% of forest areas were predicted to be lost across the whole study under the maximum development scenario (Johnson 2010). Another predictive model for shale gas development, this time in Canada, produced the same result (Racicot et al. 2014). A third landscape-scale study reported total losses, but the results of this study are difficult to use because scale of the losses was not well communicated, and loss of core forest to edge forest was not considered (Drohan et al. 2012).

While these few studies have considered landscape-scale change, various estimates of the footprint of oil and gas activity on a sub-landscape scale are published. It is important that we understand the actual of disturbance to make sense of the changes observed at a landscape scale. Well pads in two counties in Pennsylvania were found to be, on average 1.3 ha and 2 ha in size (Slonecker et al. 2012). This includes both shale gas and coal seam gas wells, through CSG well pads are noted to be smaller than shall gas well pads. In another Pennsylvanian study, shale gas well pads occupy 3.1 ha, and the average disturbance due to all infrastructure was estimated to be 8.8 ha per well (Johnson 2010). Bergquist et al. (2007) quote 1.6 ha as a typical area of disturbance (including associated infrastructure), but take the figure from a magazine article in which the source is not cited. The same magazine article suggests that well density is approximately one in every 32 ha (Clifford 2001). Williams, Milligan and Stubbs (2013) take their estimations from Broderick et al. (2011) who found that shale gas well pads alone may occupy at least 0.4 ha (if reclaimed), and may occupy more than 2 ha. Other sources estimate well pads between 1.2 ha and 2.0 ha (Drohan et al. 2012). Future development is likely to require lower well pad density (Williams, Milligan & Stubbs 2013).

Within the study area, QGC are the largest operator of CSG wells. The company is in the process of expanding operations as part of the Queensland Curtis Liquid Natural Gas (QCLNG) project. These specifications have not necessarily been used in the construction of existing infrastructure, or infrastructure built by other operators, but gives an indication of the current standards for construction in Queensland. Well pads are designed to be 100m by 100m (1 ha) initially, and 80m by 60m (0.48 ha) after partial restoration (QGC Limited 2009a). These pads are smaller than those constructed overseas or analysed in the academic literature.

The QCG proposal also outlines the size of related CSG infrastructure to be constructed as part of the QCLNG project. The land required includes 7 hectares for each field compressor station, 19 hectares for each central processing plant, 25 hectares for each water treatment plant, 30 hectares for each brine pond and 130 hectares for each brine evaporation basin (QLD Department of Infrastructure and Planning 2010). Water and gas trunk line easements were expected to be 20m – 54m wide depending on the use of the easements for other services (QLD Department of Infrastructure and Planning 2010). Access roads are designed to be 4m wide (QGC Limited 2009a). These facilities are to be built throughout the Walloon Fairway, part of which occurs inside the study area examined in the current study.

2.5 Transition Matrix

In studies of land cover change, a matrix is commonly used to catalogue changes in vegetation extent. The matrix is commonly known as a transition matrix, change matrix or cross-tabulation matrix. It is used to analyse persistence, gain and loss of area occupied by each category of land use and land cover (LULC) in a study area. In its most basic form, the matrix displays the extent of land cover (total area or percentage cover) in each category against the land cover in each category at a subsequent time snapshot. The diagonals of the matrix represent persistent land cover, and cell *j,i* represents land converted from category *j* at time one to category *i* at time two (Pontius, Shusas & McEachern 2004). Though the concept was in previous use, the seminal work of Pontius, Shusas and McEachern (2004) formally described the transition matrix, defined the conditions of its use, and proposed a method of differentiating random and non-random landscape changes.

The transition matrix is a well-established tool in analysing land cover change. It has been used to analyse naturally dynamic systems such as the Paraná River delta in Argentina (Biondini & Kandus 2006), as well as regions of widespread human-induced change such as the Hunter Valley in New South Wales (Manandhar, Odeh & Pontius 2010), Pithoragarh in Northern India (Munsi et al. 2010), the Espinal ecosystem region in Argentina (Johnson & Zuleta 2013) and Encinares de río Alberche y Cofio in central Spain (Pérez-Hugalde et al. 2011). In each study of human impacts, the drivers of change were found to be development of agricultural land, abandonment of agricultural land or development of urban landscapes. None of the studies employing a transition matrix studied the effects of extractive industries.

2.6 Impacts of Landscape Fragmentation

The impact of fragmentation on conservation outcomes for remnant vegetation is widely studied around the world. It is well recognised that quantity is not the only important factor in assessing the environmental and economic significance of remnant habitat, but that the spatial arrangement of habitat areas is also important to ecological function (O'Neill et al. 1997; Slonecker et al. 2012). Oil and gas extraction activities can significantly alter important characteristics of the spatial arrangement of remnant habitat (Slonecker et al. 2012). Fragmentation may lead to the creation of edge effects, or create barriers to migration between isolated patches. Objective number two of this work is to quantify the fragmentation of the landscape in a CSG development region in QLD, and the background understanding needed to effectively analyse landscape fragmentation is considered here.

The creation and impact of edge habitat is one of the most well-studied aspects of vegetation fragmentation and is considered one of the most important causes of stress on fragmented habitat (e.g. Murcia, 1995). It has been long recognised that edges of remnant vegetation are more susceptible to change from external stressors (e.g. Murcia, 1995). As such, edges may:

- Contain forests of altered structure (Slonecker et al. 2012);
- Contain greater non-native plant species richness and total cover than core areas (Bergquist et al. 2007);
- Provide habitat that is subject to greater predation pressures than core areas (Piper & Catterall 2004);
- Be subject to greater tree mortality and biomass loss (Slonecker et al. 2012);

- Be subject to different solar radiation, wind and moisture regimes (Murcia 1995);
- Fail to preserve the ecological integrity and wild nature of the forest (Drohan et al. 2012); and
- Attract generalist species, confining specialists to core habitat areas (Farina 1998).

The other major impact of fragmentation is the isolation of stands of remnant vegetation from one another. Each population of flora and fauna separated by the barrier effect is genetically isolated from others and less resilient to environmental stressors (Coffin 2007; Forman & Alexander 1998). Also, these populations must rely solely on habitat within an individual patch, which may or may not be of sufficient size to address their needs. Any land cover that is hostile for a species may provide a barrier to its migration between patches of remnant vegetation.

A major field of study regarding fragmentation and barrier effects is road ecology, i.e. the impact of roads on the environment (Coffin 2007). These studies are relevant because roads are a prominent feature of CSG development, and may severely fragment the landscape. Roads are hostile to various species because they produce noise and air pollution, introduce vehicles in an area where they may collide with fauna and create an environment more suitable for hunters and competitors (Coffin 2007). Edge-adverse species are either killed in the road environment, or are observed to avoid roads (Coffin 2007; Forman & Alexander 1998). Many of these impacts are correlated to traffic density, and are measured on major roadways. However, a large amount of literature shows that even narrow, unsealed roads (such as those built to service CSG infrastructure) change the microclimate in adjacent vegetation and cause impediments to migration of small animals such as beetles and spiders (Coffin 2007; Forman & Alexander 1998).

While the body of literature concerning landscape fragmentation is large, much of the data is highly species specific. It is well recognised that the analysis of landscape fragmentation is most relevant when applied to specific species (Saura & Torné 2009). Each species of plant and animal is affected by habitat isolation and edge effects according to their own characteristics, their interaction with the environment and their ability to adapt to a new environment. For example, above-ground pipelines have been demonstrated to prevent migration of large fauna in Canada (Dunne & Quinn 2009), and the size of non-forested barriers are strongly correlated to the ability of koalas to survive in small fragmented habitat areas (McAlpine et al. 2006), but these barriers don't prevent the movement of all species. It may be possible to predict species placed most at risk through a particular change to the landscape structure by studying parameters such as population size, stability in population size, dispersal ability between patches, reproductive potential and individual area requirements (Henle et al. 2004).

It is because each species reacts to environmental change differently that defining the impacts on individual species has been ruled out of the scope of this project. Instead, this work will take a general approach used by other authors whose aim is to characterise the impacts of oil and gas development generally at a landscape scale (Baynard 2011; Drohan et al. 2012; Finn & Knick 2011; Racicot et al. 2014; Slonecker et al. 2012). This study will analyse landscape change by considering a number of ecologically significant fragmentation metrics. Rather than assessing the implications of change for arbitrary species, ecosystems or vegetation types, it will draw general conclusions about whether or not significant impacts on some populations are plausible in Queensland.

2.7 Previous Studies Measuring Extent of Landscape Fragmentation

Fragmentation of land cover due to oil and gas industries is analysed in the scientific literature, though no publically available landscape-scale study specifically concerning CSG is identifiable. While studies concerning fragmentation effects of other oil and gas extraction industries in North America are useful for comparison, the current work is important in the context of CSG development and for an Australian perspective. A number of the studies from North America have taken a predictive or a retrospective approach, to determine the future or past impact of oil and gas extraction industries on landscape structure (Drohan et al. 2012; Finn & Knick 2011; Johnson 2010; Racicot et al. 2014; Slonecker et al. 2012). Each of these studies demonstrates that relatively minor losses of overall vegetation may coincide with major changes in the landscape fragmentation metrics. This finding is particularly relevant in the fulfilment of objective three of this study. Other potentially relevant bodies of work analyse the impacts of disturbance on remnant vegetation, though not necessarily due to oil and gas extractive industries. Of particular relevance to this study are the impact of roads and edge effects on vegetation (Collard, Le Brocque & Zammit 2011; Finn & Knick 2011; Murcia 1995; Neel, McGarigal & Cushman 2004; Reed, Johnson-Barnard & Baker 1996).

Many of the studies that measure fragmentation in regions of concentrated gas extraction have been conducted in Pennsylvania (Drohan et al. 2012; Johnson 2010; Slonecker et al. 2012). In one such study of infrastructure development for conventional natural gas extraction, the development removed double as much interior forest as forest lost overall, and created as much forest influenced by edge effects as forest lost overall (Slonecker et al. 2012). Similarly, Drohan et al. (2012) studied fragmentation due to shale gas development in Pennsylvania. Some direct loss of core forest areas was identified due to shale gas development, but landscape structure metrics and losses to edge forest were not analysed.

Drohan et al. (2012) provided more diverse analysis of the impacts of fragmentation due to gas extraction in Pennsylvania. They mentioned, in passing, the impacts of fragmentation on agricultural areas and differences in management of wells on public and private land in Pennsylvania. Abandonment of agricultural land surrounding shale gas development areas was hypothesised, as occurs in rural areas that are fragmented by urban development (Drohan et al. 2012). Griffith and Severson-Baker (2003) also briefly considered the impacts on agriculture, but the firm focus of the literature is on fragmentation in forested areas, particularly core forests. Drohan et al. (2012) also considered the impact on streams by measuring the average distance between well pads and watercourses, though the distances were not quoted.

Drohan et al. (2012) were a major influence on a similar study in Canada that assessed previously fragmented regions using predictive models for shale gas development. While forest areas were predicted to reduce by <1% across the whole study area there was predicted to be an increase in the number of forest patches of up to 21%, and a decrease on forest patch size by approximately 10% (Racicot et al. 2014). Much of the impact was due to pipeline construction, which was considered to require 18m wide clearings (Racicot et al. 2014).

One study into the impact of oil and gas developments in Wyoming conducted by Finn and Knick (2011) fits closely with the aims of this work. Apart from calculating direct losses of vegetation, Finn and Knick (2011) were able to demonstrate decreases in average patch size and core areas and increases in habitat edge, in line with oil and gas development, over a period of time between 1900 and 2009. While only modest changes were shown on a landscape scale, development hotspot areas, defined as region within 0.2km of a well, were also tested. Within these regions, average patch size reduced by 45%, core habitat areas (buffer 60m) declined by 55.6% and habitat edge increased by 33%. Such large responses not surprising, considering that a 0.2km buffer represents just 12.6 ha, and therefore a well pad alone might occupy more than 10% of that area. Impacts at a winder scale were present, but much smaller. A noted difficulty in this work was a lack of information on oil and gas infrastructure other than roads. In some studies, methods of predicting locations for infrastructure such as roads and pipelines were developed (Finn & Knick 2011; Racicot et al. 2014). In this study, hand digitisation of the CSG road network, used for a previous study, will allow for a more complete analysis of the impacts of all CSG infrastructure.

The impact of road density and well pad density on fragmentation was measured in a number of studies (Bi, Wang & Lu 2011; Drohan et al. 2012; Finn & Knick 2011; Racicot et al. 2014). While Drohan et al. (2012) used the length of roads constructed as a measure of fragmentation, it was Bi, Wang and Lu (2011) who demonstrated a correlation between the length of roads constructed, density of wells and landscape fragmentation in an area impacted by conventional gas extraction in China. In particular, more regular area-weighted mean patch shape was correlated to a greater road density and well pad density was strongly positively correlated with the number of patches.

Edge effects have been studied extensively, though not necessarily in studies related to energy extraction activities. The most relevant study of the impact of edge effects, specifically due to CSG, was completed in the Powder River Basin of Wyoming (Bergquist et al. 2007). This study did not consider the extent of fragmentation, or the specific activities that caused change, but showed that vegetation adjacent to CSG developments was altered in density and species composition. Particularly, increased invasion by non-native species was observed. Objective two of this study is to measure the fragmentation occurring in the study area. The research conducted by Bergquist et al. (2007) is significant because it indicates that, where fragmentation due to CSG occurs, demonstrable edge effects are plausible.

The size of the zone altered by edge effects is site specific and highly variable (Murcia 1995). Recently, one highly relevant study in mixed

Brigalow vegetation communities in Queensland found that edge effects, in forest stands adjacent to agricultural areas, did not cause a reduction in species diversity or change in community composition, when compared to core areas of that vegetation remnant (Collard, Le Brocque & Zammit 2011). Edge effects of fragmentation may not be as significant an issue in the Brigalow Belt as in other parts of the world. Many studies reviewed by Murcia (1995) found the edge zone to be less than 50m wide, though this review found many of the studies not to be rigorous enough to analyse the complexities of edge effects, to study the effects at a fine enough scale or to make general conclusions about the principles of edge effects. Despite the difficulty in defining and measuring edge effects, an arbitrary buffer is chosen in fragmentation studies to estimate the extent of edge effects. Some consensus has grown around an arbitrary width of 100m (Drohan et al. 2012; Racicot et al. 2014). In other studies, smaller arbitrarily chosen buffers of 50m (Reed, Johnson-Barnard & Baker 1996), 60m (Finn & Knick 2011) and 90m (Neel, McGarigal & Cushman 2004) have been used.

2.8 Methods of Measuring Fragmentation

The importance of the choice of fragmentation metrics for monitoring ecological function, and the complexity in choosing appropriate metrics to measure the impacts on landscape structure, is well recognised. Metrics must be carefully chosen to be (McGarigal n.d.-b, n.d.-a; Neel, McGarigal & Cushman 2004; O'Neill et al. 1997; Slonecker et al. 2012):

- Truly indicative of the landscape;
- Applicable to the particular ecological processes under consideration;
- Meaningful in analysis (sensitive to landscape differences but not classification errors);
- Comparable (must be considered when comparing images of different resolutions and scales); and

- Not mutually correlated (mathematically by representing the same information in different ways, or empirically due to correlations in the physical landscape between factors that are evaluated by different metrics).

Despite academic attempts to develop sets of metrics that, together, are sufficient and necessary to describe a landscape, these sets of metrics have not been widely adopted (Baynard 2011; Riiters et al. 1995). Further, standards have not been developed, by industry or government, to guide the choice of metrics for investigations into habitat fragmentation due to extractive industries (Baynard 2011; McGarigal n.d.-a). Neel, McGarigal and Cushman (2004) suggest that metrics should be categorised on a continuum from being completely correlated to patch area to being completely correlated to aggregation, and several metrics chosen from across the continuum.

Without a common standard, the sets of metrics chosen by researchers do not match those in other similar studies. Table 1 summarises which landscape metrics have been chosen to describe fragmentation in studies on fragmentation due to gas extraction, or proposed as standard sets of metrics for that purpose. The lack of correlation between studies makes it difficult to select metrics that will allow for effective inter-study comparison, or to link the results of this study to others in the past. Since a large number of common class metrics show little correlation to one another and a broad understanding of landscape structure is required in this work, a fairly large number of different types of metrics will need to be calculated (Neel, McGarigal & Cushman 2004).

Table 1: Matrix showing the choice of fragmentation metrics used in other studies of landscape change due to oil and gas development

	Total Area	Land Cover - per cent of area	Number of patches	Average patch area	Largest patch index	Normalised patch area, square model	Median patch area	Total edge	Edge density	Average perimeter-area ratio	Patch shape	Area-weighted mean patch shape	Mean fractal index	Contagion	Shannon contagion	Evenness	Interspersion and juxtaposition index	Core area	Core area % of area	Core area/edge area/patch/perforated	Edge area	Edge area % of area	NDVI change	Production density	Number of rivers crossed by roads	Length of linear feature (road)/linear feature density	Number of attribute classes	Patch perimeter area scaling (fractal estimator of patch topology)
Baynard (2011)																		■			■		■	■	■			
Bi et. al. (2011)			■		■							■					■							■		■		
Drohan et al. (2012)																				■						■		
Finn and Knick (2011)	■	■		■					■		■							■								■		
Racicot et al. (2013)			■	■														■								■		
Riiters et al. (1995)						■				■					■												■	■
Slonecker et. al. (2012)	■	■	■	■			■	■					■	■		■			■			■						

2.9 Software Tools for Measuring Fragmentation

Researches in vegetation fragmentation occasionally identify the tools that they use to determine the fragmentation metrics. FRAGSTATS is the most common tool used to make general calculation of landscape indices. It is designed to measure composition and configuration metrics at cell, patch scale, patch class scale and landscape scale for a broad range of applications (McGarigal n.d.-a). The software calculates statistics that characterise individual patches, patch classes and the landscape mosaic

(McGarigal n.d.-a). One application of FRAGSTATS is in the assessment of the impacts of extractive industries on landscape vegetation fragmentation. In this field of study the software has been applied to research on natural gas extraction in Pennsylvania (Slonecker et al. 2012), oil and natural gas development in Wyoming (Finn & Knick 2011) and oil extraction in China (Bi, Wang & Lu 2011).

Many software options are available, and the development of new tools is a continuing field of development (Saura & Torné 2009). Other recent land cover fragmentation studies have used ATtILA, which is an extension to ArcView developed by the USEPA (Slonecker et al. 2012), or have used spatially implicit models of landscape metrics. The implicit models have been superseded by spatially-explicit GIS models such as those used by FRAGSTATS (Didham & Ewers 2012; Racicot et al. 2014). FRAGSTATS is considered a good choice for the current study because of its previous widespread use, versatility and applicability.

2.10 Summary

The academic basis for a study of land cover and fragmentation change is well established. Research in landscape ecology has established the importance of extensive and appropriately arranged remnant vegetation for the survival of flora and fauna populations and the overall health of the environment. Further, the regions of Queensland under heavy CSG development are already at high risk due to their history of disturbance. Various tools have been established to analyse land cover change and fragmentation, including theoretical methods (e.g. land cover matrices and fragmentation metrics) and software (e.g. ArcGIS and FRAGSTATS). These tools are well tested, reliable, and readily applied in this study, although there is a lack of consensus around the choice of fragmentation metrics to use in a study such as this.

In the context of Chapter 2, a landscape-scale study into the impact of CSG on land cover extent and configuration in Australia is timely and important to ensure sustainable development. While some studies have applied the theory of habitat loss and fragmentation to disturbance due to oil and gas development, there are very few studies of the impacts of CSG on land cover loss and fragmentation in the Australian environment. Overseas studies of the impact of CSG are not widely published, and are of limited relevance in Australia. The growth of the industry seen in the 15 years to 2013 is predicted to continue, particularly with the creation of an export market, and development of the QCLNG project. Through this project, the theory of vegetation fragmentation will provide insight into the effects of CSG development in Australia.

3 Methods

3.1 Introduction

The 'Methods' chapter provides a description of the means by which this research was undertaken. It includes a description of the study area, sources of data, empirical and statistical methods. Each of the choices made in designing the experiment are justified, particularly where there is divergence from the methods used in other similar studies, or a lack of consensus in the methods used by other researchers.

3.2 The Study Area

The study area has been chosen to include some of the most heavily developed CSG fields in Australia. It is shown in its regional context in Figure 1. The defined area covers 3.902×10^5 hectares in southern Queensland, mostly in the Western Downs Regional local government area and partially in the western parts of the Toowoomba Regional local government area. The region is bounded by the parallels S 26°43', S 27°35', E 150°17' and E 151°12', includes the township of Kogan, and is close to Dalby and Chinchilla. It is wholly within the Condamine River catchment, and has boundaries defined by the extent of a number of major co-adjacent sub-catchments (Wieambilla Creek, Wilkie Creek, Braemar Creek, Kogan Creek and Wambo Creek). The Condamine River itself roughly defines the northern boundary of the study region.

Agricultural land uses predominate in the study area. The northern and northern-eastern parts of the study area, on the river flats, are dominated by irrigated cropland. Further south agricultural pursuits focus on grazing. Significant areas are also used for production forestry and rural residences (QLD Department of Science 2012). Gas wells have been drilled across land use types. In 2013, the region contained 1562 CSG wells, 105 of which were exploration wells. Two-thirds (1007) of the wells were operated by the Queensland Gas Company (QCG), with nine other operators involved in the region. The great majority of CSG activity in the region has occurred since 1999. Only one of the wells predates the study period (drilled in 1995). The region also contained 33 non-CSG wells, however these were exploration wells suck in the 1960s, 1970s and 1980s, and were not considered in analysis.

Much of the CSG infrastructure in the study area that has been built and operated by QCG contributes to the Queensland Curtis Liquid Natural Gas (QCLNG) project. Within the Walloon Fairway, in which the study area is substantially located, QCG has constructed a large amount of infrastructure within their 2010 to 2014 construction timetable. Many of these new infrastructure developments fall within the study area and are analysed as part of this work. Infrastructure includes well pads, roads, field compressor stations, pipelines, central processing plants, dehydration facilities, operation camps, offices, warehouses, water gathering lines and water treatment facilities. New power lines connected to third party substations service these facilities.

The study area also contains other gas-related infrastructure. The Darling Downs Gas-Fired Power Station is operated by Origin Energy and provides 630MW of base-load power to the electricity grid (Origin Energy n.d.). The facility was constructed between 2007 and 2010, during the study period (Origin Energy n.d.). Power lines connected to the power station were included in the file of digitised linear infrastructure and therefore, unavoidably, included in the analysis.

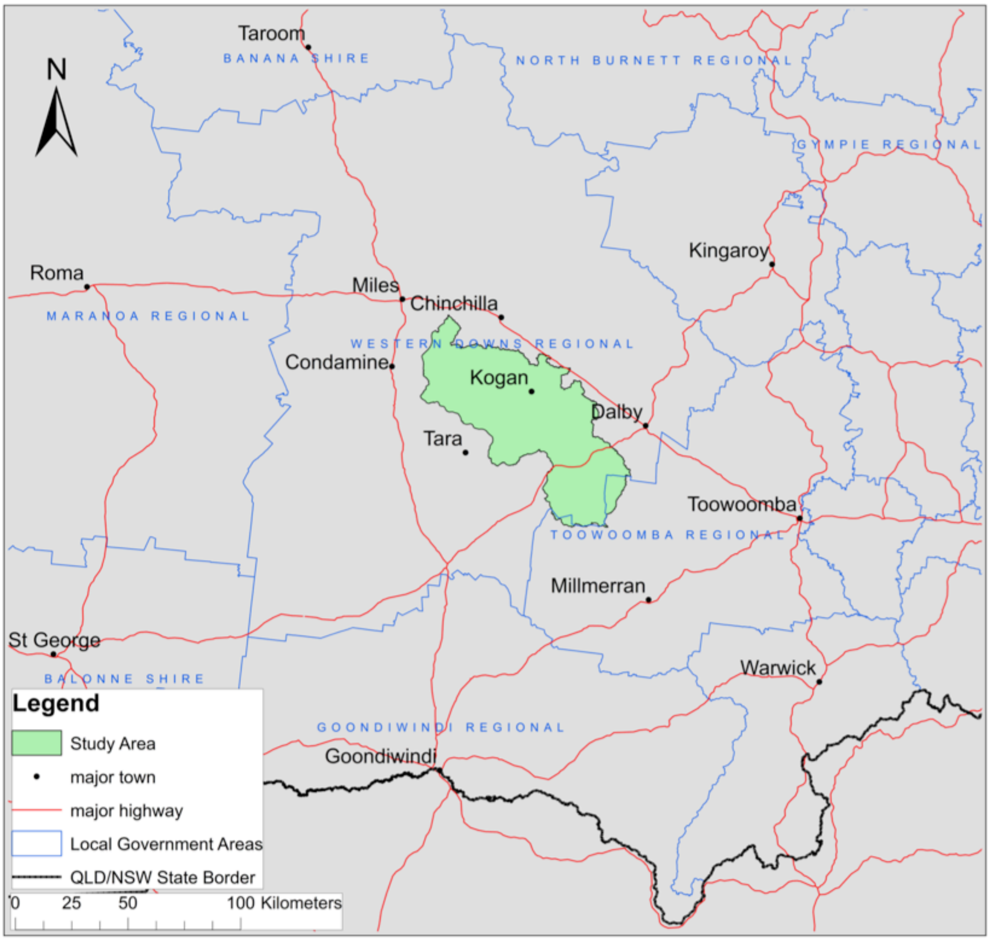

Figure 1: Map showing the study area in its regional context.

3.3 Resource Requirements - Data Capture and Acquisition

All data and imagery required for the project were publically available on the Internet. The datasets required for the project are set out in Table 2 (main analysis) and Table 3 (context map). The satellite imagery from 1999 is shown in Figure 2 and the satellite image from 2013 in Figure 3. Both images are shown with colours corresponding to the same wavelengths. Having been taken from different generations of satellite, in order to create images with the same wavelength allocations to each colour (red, green and blue respectively), bands 5, 4 and 3 are used for the 1999 image and bands 6, 5 and 4 for the 2013 image.

Table 2: Datasets used in the analysis.

Theme	Description	Source
LANDSAT 4 imagery	*Thematic Mapper* satellite imagery of the study area taken in 1999.	U.S. National Aeronautics and Space Administration et al. (1999).
Landsat 8 imagery	*Operational Land Imager* satellite imagery of the study area taken in 2013.	U.S. National Aeronautics and Space Administration and U.S. Geological Survey (2013).
Classified images of the study area	Binary classification of the vegetated and non-vegetated parts of the study area, derived from LANDSAT 4 and Landsat 8 imagery described above.	Apan (2014b).
Study area boundaries	An aggregated boundary map based on Condamine River sub-catchment boundaries defined by the Condamine Alliance.	Apan (2014a).
Locations of CSG wells	Spatial information and meta-data for all government-registered CSG wells sunk before August 6, 2013.	QLD Department of Natural Resources and Mines (2013).
Petroleum lease areas	Spatial extent of land under petroleum leases granted by the Queensland government before 2012, and land included in proposals under consideration of the Queensland Government in 2012. Granted leases were extracted from the file.	QLD Department of Natural Resources and Mines (2012).
Non-CSG well locations, gas pipeline locations and metadata	Locations of all conventional gas wells and location of gas pipelines (for CSG and conventional gas) in Queensland.	QLD Department of Natural Resources and Mines (2014c).
Drainage lines	Drainage lines extracted from the 1:250000 topographic map data provided on Map Connect (The GIS data viewer for Geoscience Australia).	GEODATA (2006).
Physical position of roads	Position of the centre-line of all roads in Queensland (based on cadastral surveys and improved with satellite data).	QLD Department of Natural Resources and Mines (2010a).
Position of CSG-related roads and linear infrastructure	Position of roads (including some pipelines and power lines) obtained by hand-digitisation of LANDSAT 4 and Landsat 8 images.	Apan (2013).
Land use	Survey of the use of each land parcel in the Condamine River Basin in 2006.	QLD Department of Science (2012).
Digital Cadastral Data Base (DCDB)	2006 cadastral boundaries, including information on features contained within land parcels for some holdings.	QLD Department of Natural Resources Mines and Water (2006).

Table 3: Datasets used to build the context map in Figure 1

Theme	Description	Source
Local government boundaries	Location of local government area boundaries in Queensland, and names of local government areas.	QLD Department of Natural Resources and Mines (2014b)
Major roads	Location of major Highways in Queensland.	QLD Department of Natural Resources and Mines (2013)
QLD place names	All place names in Queensland, location of all named places in Queensland, and type of place. The major town names and locations were extracted from the dataset.	QLD Department of Natural Resources and Mines (2014a)
QLD state border	Location of Queensland's land borders.	QLD Department of Natural Resources and Mines (2010b)

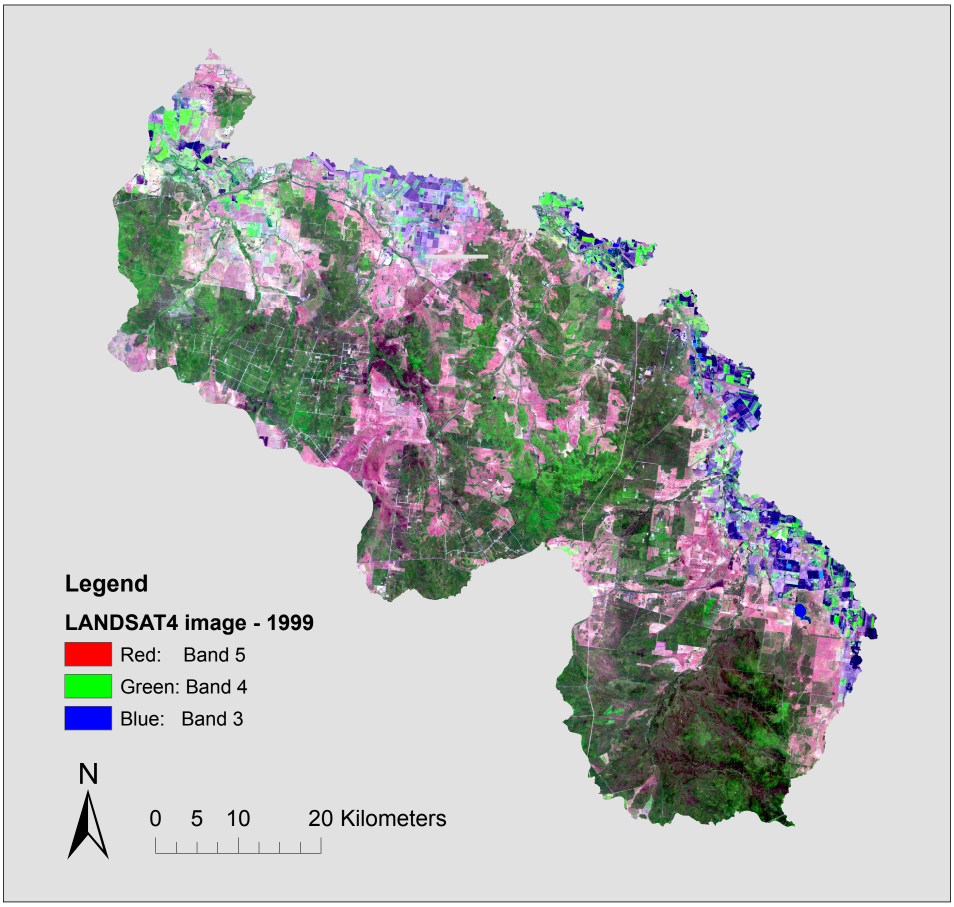

Figure 2: LANDSAT 4 imagery of the study area taken in 1999

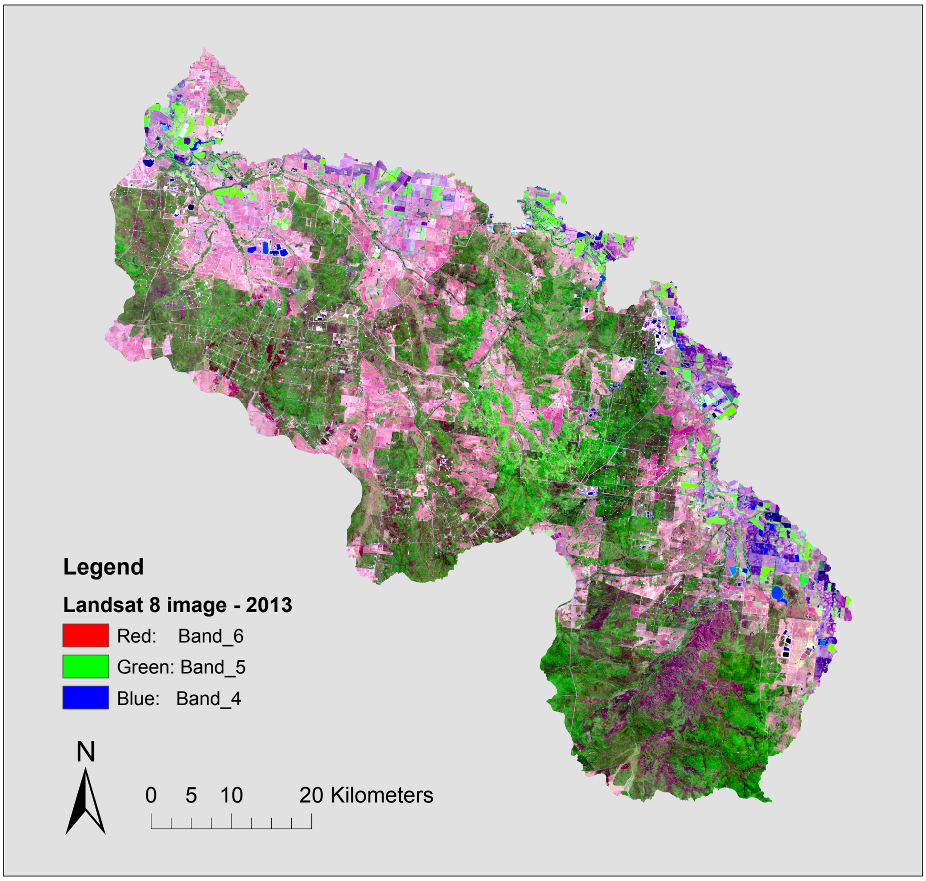

Figure 3: Landsat 8 imagery of the study area taken in 2013

Each of the datasets in Table 2 and Table 3 were chosen because they were reliable and readily available for the project. LANDSAT 4 and Landsat 8 provided data at least as satisfactory for the project as could have been obtained from the major alternative, SPOT (Satellite pour l'Observation de la Terre) imagery. LANDSAT 4 and Landsat 8 imagery were chosen in preference to SPOT principally because of better availability. Images from the same LANDSAT satellite programs were not available across the study period, due to the launch of new satellites and decommissioning of older satellites. However, the imagery from 1999 and 2013 are directly comparable.

Other than the satellite imagery, most of the datasets required for the project were obtained through various Queensland Government departments, Geoscience Australia (for drainage lines) and The

Condamine Alliance (for sub-catchment boundaries). These were the only publically available, pre-collected sources of the necessary data and, in most cases, were the only plausible sources of data due to inaccessibility of the research sites. The agencies from which the data are sourced are reputable and are likely to provide reliable data.

The software for the project was readily available. Most of the analysis uses ArcGIS 10.2.0.3348 software, which was available through the University of Southern Queensland (USQ) (ESRI, 2013), and FRAGSTATS 4.2 software, which is available for free download from the Internet (McGarigal, Cushman & Ene 2012). QLD Globe datasets required Google Earth, which is pre-installed on USQ computers (version 7.1.1.1888) (Google Inc., 2013).

3.4 Data Processing and Analysis

3.4.1 General Principles

Each of the objectives identified in part 1.6 will be addressed by following the procedure set out in the flow chart in Figure 4, which provides a summary of all the procedures undertaken. The chart shows original datasets in green (rectangle), outputs in red (oval), intermediate datasets in blue (rectangle with bevelled corner) and the processes undertaken are described as annotations on each of the arrows. All preliminary data processing was completed using ArcGIS 10.2.0.3348 (ESRI, 2013).

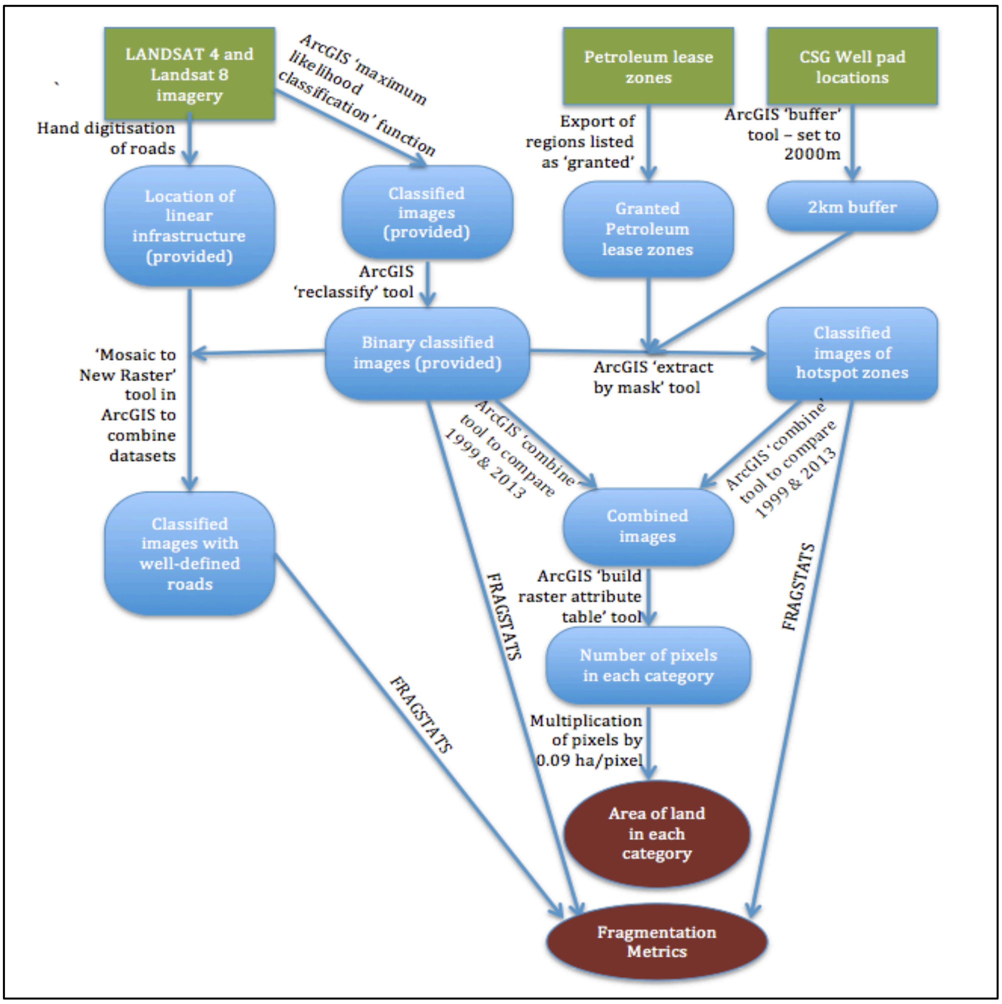

Figure 4: Flow chart showing scheme of analysis

The first objective requires a comparison of total land cover before CSG development in the study area, and after some development has occurred. It is purely a measurement of remnant habitat extent. Despite its limitations and simplicity, it is commonly used to assess the environmental health of an eco-region. The relevant methods are discussed in part 3.4.2.

The second objective requires a more complete analysis of landscape health by considering the spatial arrangement of remnant vegetation. The information gained by this analysis is more ecologically relevant than total landscape change. It also demonstrates the effect of the pervasive but partial occupation of the landscape by CSG infrastructure better than a simple land cover change analysis. The analysis of fragmentation is described in part 3.4.3.

The third objective is essentially about explaining the causes for land cover change and fragmentation. There are various activities taking place in the study area, and each potentially impacts on the land cover. The methods used to elucidate the causes of change are described in parts 3.4.4, 3.4.5 and 3.4.6.

3.4.2 Quantification of Land Cover Change

All analytical work to quantify the amount of land cover change in the study area used ArcGIS 10.2.0.3348 (ESRI, 2013). Landsat images taken of the same region in 1999 and 2013 were classified according to the presence or absence of woody vegetation. This classification was done using the 'Maximum Likelihood Classification' tool in ArcGIS, followed by an application of the 'reclassify' tool to reduce the number of classes in the image from eight to two. The images were checked to ensure that a 20% classification error was not exceeded. These classified images were pre-prepared by Apan (2014b), and made available for the current work. Land cover change between classified images was analysed using the 'Combine' tool to create a map (Figure 5) showing deforestation, afforestation, persistent woody vegetation and persistent non-woody vegetation.

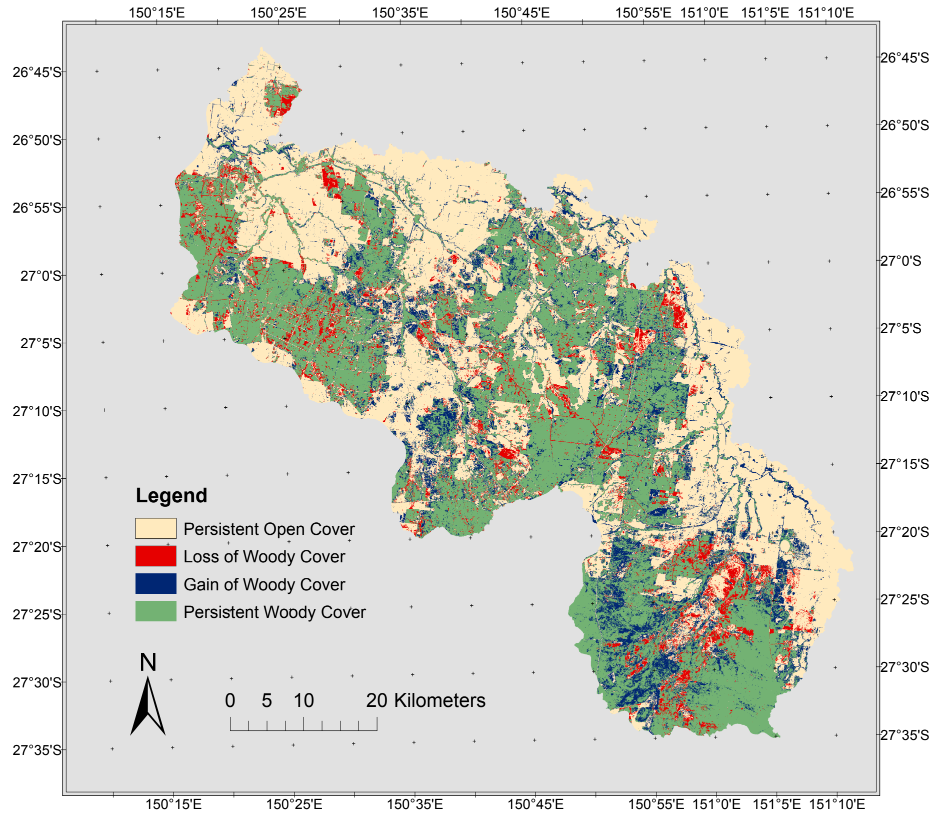

Figure 5: Map showing regions of persistence, gain of woody cover and loss of woody cover

After calculating the number of pixels in each category in the classified image, change matrices were prepared using methods drawn from previous studies (Manandhar, Odeh & Pontius 2010; Pontius, Shusas & McEachern 2004). A method to compare expected random change and actual change proposed by Pontius, Shusas and McEachern (2004) was found to be ineffective for analysis of binary change. However, swap changes were calculated and analysed, according to the literature on the analysis of land cover change. Since gross gains and losses are not fully accounted for in calculations of net gain or loss, swap changes are calculated using equation 1 (Manandhar, Odeh & Pontius 2010):

$$Swap = total\ change - net\ change$$

(Equation 1)

Where $total\ change = (gross\ gain + gross\ loss)$

$net\ change = (gross\ gain - gross\ loss)$

3.4.3 Measurement of Vegetation Fragmentation

Analysis of fragmentation of the landscape uses FRAGSTATS v4.2 (McGarigal, Cushman & Ene 2012). FRAGSTATS is the most common tool used to calculate landscape indices in the published literature. The software has been applied to research on natural gas extraction in Pennsylvania (Slonecker et al. 2012), oil and natural gas development in Wyoming (Finn & Knick 2011) and oil extraction in China (Bi, Wang & Lu 2011). Other software packages have been used for a similar purpose, but are less widely recognised, and do not provide obvious advantages for this project (Saura & Torné 2009; Slonecker et al. 2012).

The categorised LANDSAT 4 and Landsat 8 images are analysed for a range of metrics at the class level. An 8-cell-neighbourhood rule and a 'no sampling' strategy was used. The various choices of metric are justified in Table 4. All metrics based on edge effects assumed an edge depth of 90m (3 cells). This edge depth was chosen to be consistent with literature on the topic, and an integer multiple of the cell size used in this study. The coefficient of variation was calculated for all indices where an average was taken. It provides a mean-weighted indication of the amount of variability in the metric (assuming a normal distribution in the landscape).

Table 4: Patch metrics considered in this study

Class metric	Explanation and Justification of Choice.
Number of patches (patch density)	This is a simple count of the number of vegetated regions completely separated from one another. It is a basic comparative measure of the degree to which remnant vegetation is fragmented. By dividing the number of patches by the area in which they occur, the patch density is determined. This weights the metric to the total size of the study area, which is useful for comparison between areas of different size, such as between hotspot areas within the current study area.
Mean patch area ± coefficient of variation	The patch area is the most basic and useful piece of information in categorising the impact of fragmentation in an environment (McGarigal n.d.-a). Combined with the number of patches it is possible to ascertain the level of fragmentation of the environment. Many species have minimum area requirements, and therefore this metric is highly ecologically relevant (McGarigal n.d.-a).
Total edge	This metric is total length of edge around a particular land cover class in the study area (in this case not calculated to include edges along the boundary of the study area). It is an indicator of the extent to which fragmentation of the landscape has altered the nature of the remnant vegetation by creating edge-affected forest. Edge effects are a significant focus of study in landscape ecology and the total edge metric allows an application of that body of knowledge to this work. Therefore, total edge is a fundamental metric in understanding class fragmentation (McGarigal n.d.-a). The metric may be weighted to the size of the study area by calculating edge density, which is useful for comparing different sized areas (McGarigal n.d.-a).
Total core area	Total core area is the average core area per patch (not per disjunct core area) (McGarigal, Cushman & Ene 2012). Just as edge density is an indicator of the extent of alteration of remnant vegetation, the total core area is an indication of the extent of the intact remnant vegetation. Total edge (expressed as edge density) is a linear measure, while total core area is a measure of area. Analysis of this metric works in conjunction with the total edge. Total core area may be expressed as a density in order to compare between landscapes of different size.
Number of disjunct core areas	This metric measures the fragmentation of core vegetation. It is analogous to the number of patches, if edge vegetation is considered inappropriate for habitation by a species. Therefore it is relevant to the effects of fragmentation on core-habitat-obligate species. More than one disjunct core patch may occur in a single vegetated patch if the shape of the patch is irregular. It is therefore relevant to analyse this metric as well as the number of patches. The metric may be expressed as a density for comparison between areas of different size.
Shape index ± coefficient of variation	Provides an indication of the shape of the patch. Shape influences the extent to which edge effects impact on core areas. The index measures the complexity of a shape compared to a standard square containing the same area, and is therefore not area dependent. The metric was chosen over other shape metrics because it is simple and widely applicable in analysis but is not impacted by the absolute size of the patches. A value of 1 indicates that the patch is a square, which larger index values indicating greater complexity.
Mean Euclidean nearest neighbour distance ± coefficient of variation	The creation of barriers to population connectedness through patch isolation is an impact of habitat fragmentation equally as important as the creation of edge effects. The Euclidean nearest neighbour distance is the simplest measure of isolation, and one of the most widely used (McGarigal n.d.-a). The major weakness of the Euclidean nearest neighbour distance is that it is not highly ecologically significant, since the nearest patch may not be large enough to support a migrating organism. The commonly used alternative, proximity index, which weights isolation according to patch size for patches within a predefined search radius, is not used in this study. The metric species-specific, and so a relevant search radius could not be chosen in this study. The coefficient of variation of Euclidean nearest neighbour distance is used as a measure of patch dispersion (landscape heterogeneity) (McGarigal n.d.-a).

There are a number of metrics that are not applicable in this study. Contrast, similarity, interspersion and diversity metrics were not calculated as the classification of the image was binary, and therefore information about the nature of each class was lost in the process of classification (Neel, McGarigal & Cushman 2004). For the same reason, class metrics (statistics regarding the nature of a class as a whole) are chosen over metrics that characterise the landscape (all patches regardless of class). Individual patch metrics are not considered, as the average patterns across the study area are most important in this study. Metrics are calculated for forested patches, as opposed to the inverse, since ecological habitats are the focus of this study. Specific measures of connectivity are not calculated as they are not well used, and the measures of isolation will allow for analysis of connectivity. Analysis of road length was included to align this study with others that have used the same metric (Bi, Wang & Lu 2011; Drohan et al. 2012; Finn & Knick 2011; Racicot et al. 2014).

3.4.4 Definition and Analysis of Hotspot Areas

Parts of the study area under more intense CSG development were tested separately for fragmentation and land cover change. Parts of the classified image under granted petroleum leases (GPL) and within 2km of a gas well were extracted from the total area, using the ArcGIS tool ‘extract by mask’, and analysis was completed on the smaller regions. The impact in hotspot regions could be compared with change in the broader region. The extent of the area under granted petroleum leases is indicated in Figure 6 and the area within 2km of a gas well indicated in Figure 7. Approximately 61.6% of the study area is within 2km of a CSG well and 63.0% of the study area was covered by a GPL in 2012.

Despite a precedent for the use of a 0.2km buffer by Finn and Knick (2011), broader definitions were chosen to take into account the impact of other infrastructure on the landscape around the wells. The choice of a

2km buffer is arbitrary but is intended to define the hotspot as a continuous region of heavy development, rather than a series of regions around individual sites. Each hotspot region is a more tightly defined, but still whole, landscape. This philosophy was chosen because it is already known that, at a small enough scale, CSG developments require clearing of the landscape. It is at a broader scale that the impacts need to be determined.

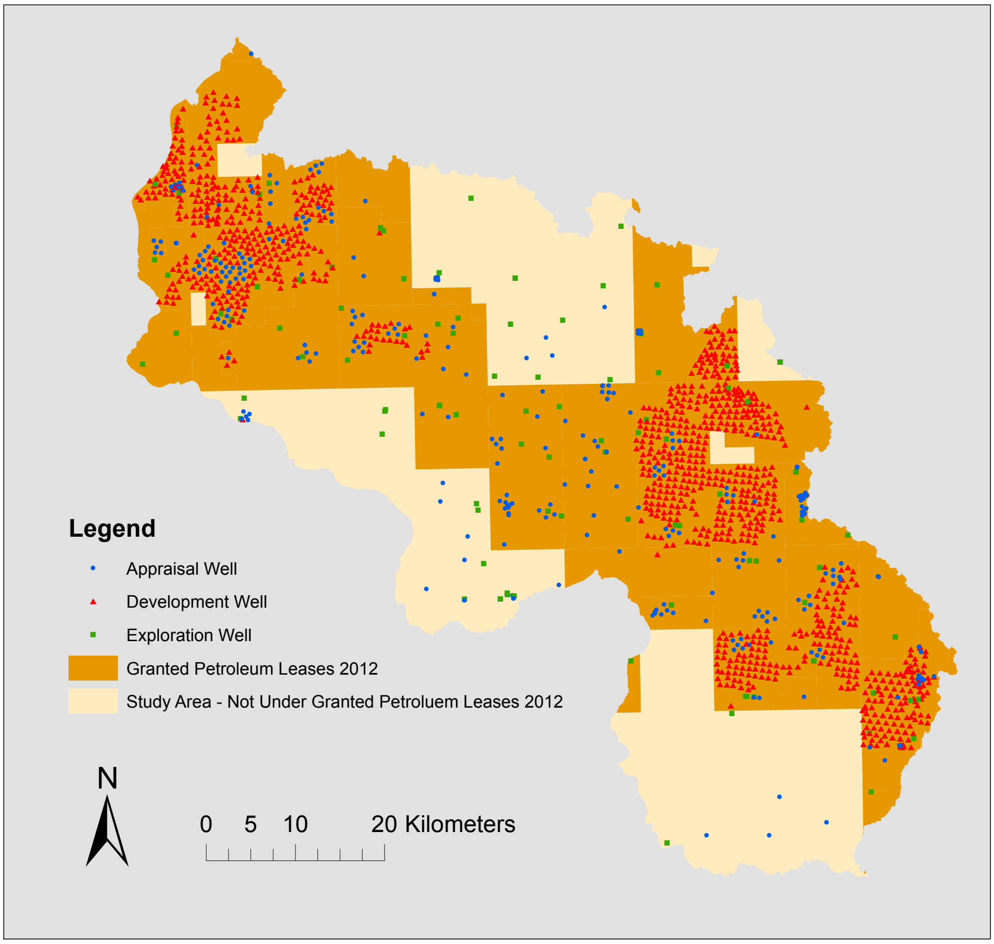

Figure 6: Regions within the study area under Granted Petroleum Leases in 2012

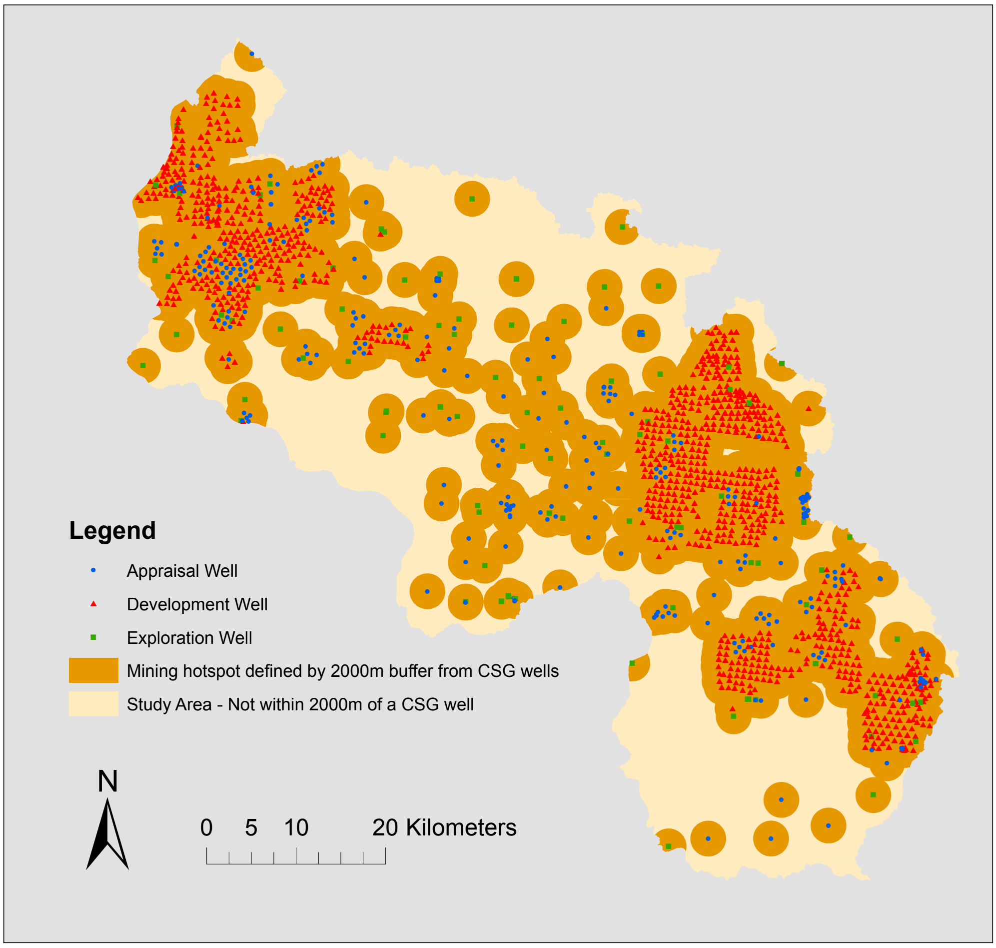

Figure 7: Regions within the study area within 2km of a CSG well in 2013

3.4.5 Creation and Analysis of Images with Well-Defined Roads

Roads and other linear infrastructure features are major contributors to vegetation fragmentation. However, continuous lines of adjacent cells assigned as clear land corresponding with identified linear infrastructure were not always visible on the raw classified image. To rectify this issue, a new set of images were produced, in which cells containing identified roads were assigned as clear land regardless of the true width of the clearing, covering of the clearing by overhanging trees or classification errors. A comparison of a region of the study area under particularly intense CSG development before and after this transformation is shown in Figure 8. The left hand side (Figure 8a) shows that larger clearings, such as those created for well pads, were identified in the classification of the Landsat picture, but the right hand side (Figure 8b) shows that an overlay of the roads on the classified image was necessary to indicate the full extent of fragmentation due to CSG development. Similar concepts have not been used elsewhere in the literature, but could be easily adopted to improve the reliability in the calculation of landscape metrics from automatically classified images.

Figure 8: Comparison of a part of the study area showing the original 2013 classified region on the left (8a), and the same region in 2013 after cells containing identified roads were designated "cleared" on the right (8b).

The method used to create the modified images relied on previously digitised linear infrastructure, such as roads. Linear infrastructure found in the 1999 and 2013 satellite images but not on the Queensland Government roads dataset (QLD Department of Natural Resources and Mines 2010a) were hand digitised for the study area by Apan (2013) and made available for this study. 'On-screen digitising', a manual process for defining the locations of features in an aerial or satellite photo, was used to create the datasets. The features within the dataset correspond to roads, power lines and gas pipelines, mainly constructed in conjunction with CSG developments. Each of the digitised linear infrastructure files is converted from a shape file to a raster image with the same resolution as the classified image, and snapped to the same grid as the classified image. The linear infrastructure was given a value of '0' to correspond to the cells classified as cleared land. The 'Mosaic to New Raster' tool was used to overlay the roads onto the classified image.

3.4.6 Analysis procedure

The measurements of land cover change and fragmentation have been calculated across the three spatial regions (total study area, 2km buffer zone and GPL areas), and at two time snapshots (1999 and 2013). Land cover and fragmentation data was compared between time steps for each of the three defined regions, and between the defined regions at each time step. Analysis of fragmentation measured in the classified image with well-defined linear infrastructure is presented in parallel, as an alternative to the analysis of the original images. Analysis regarding the differences between the two approaches provides an understanding of the effect of clearly defining the roads on the results, and provides some indication of the scale of impact of CSG development in the landscape. Finally, visual inspection of the images is conducted to determine the causes for change in larger patches of altered land cover, as part of the fulfilment of objective number three of this study.

3.4.7 Methods Associated with Other Miscellaneous Statistics.

Length of roads constructed in association with CSG development was determined from the hand-digitised linear infrastructure dataset, combined with the QLD government main roads dataset (Apan 2013; QLD Department of Natural Resources and Mines 2010a). The lengths of each line were calculated using ArcGIS. The individual lengths were exported to Microsoft Excel and the sum of the data was taken as the total length of roads in the study area. While the linear infrastructure dataset included pipelines and power lines, these were not partitioned in the dataset, and could not be easily removed. Regardless, these facilities are marginally associated with the industry and roads to access these facilities are likely to follow similar alignments.

The number of wells built in forested areas was determined by converting the areas categorised as 'forested' in the 1999 classified image from a raster to a polygon. The polygons were used to mask CSG wells in the CSG well location file, so that CSG wells within the polygons could be extracted from the original file. Inspection of the new attribute table indicated how many CSG well were located in the area defined as 'forested' in 1999. This transformation did not consider wells that existed within a specified distance of a forest edge (as in Drohan et al. (2012)), were partially constructed on pads that impacted on forested areas or were connected to linear infrastructure that required clearing of vegetation.

3.5 Summary

There are strong precedents for the general methods of analysis used in this project. Chapter 3 set out the framework in which this analysis is to be carried out, and explains the choice of methods, especially when they diverge from previous studies. The method chosen involves computer analysis of classified LANDSAT 4 and Landsat 8 images, to determine land cover change and fragmentation. Land cover change is determined using the 'combine' function in ArcGIS, while fragmentation is analysed by calculating a range of metrics using FRAGSTATS. Fragmentation metrics have been chosen to allow a broad understanding of fragmentation in the study area. Analysing smaller parts of the study area, and the same regions with distinct road clearings, will provide a better understanding of the processes in the landscape.

4 Results

4.1 General Findings

Well pad density in the study area in 2013 was found to be 249.8 ha/well. There were no wells in the study area in 1999. Of the 1,562 CSG well in the study area, 574 were constructed in cells classified as 'forested' in the 1999 satellite data. The length of roads in the study area increased from 3,434.7 km in 1999 to 6,824.5 km in 2013 (97% increase). Figure 9, which uses a combination of roads from the Queensland Department of Transport and Main Roads and from a hand digitisation process of linear infrastructure, shows that this road development has occurred primarily in CSG development areas. This assessment agrees with the analytical analysis of read length within hotspot areas. Within 2km of CSG wells, road length increased from 2,142.6 km in 1999 to 5,444.4 km in 2013 (154% increase) and well pad density has increased to 153.9 ha/well. Within GPL, the total length increased from 2,242.3 km in 1999 to 5,436.5 km in 2013 (142% increase) and well density in 2013 was 157.5 ha/well.

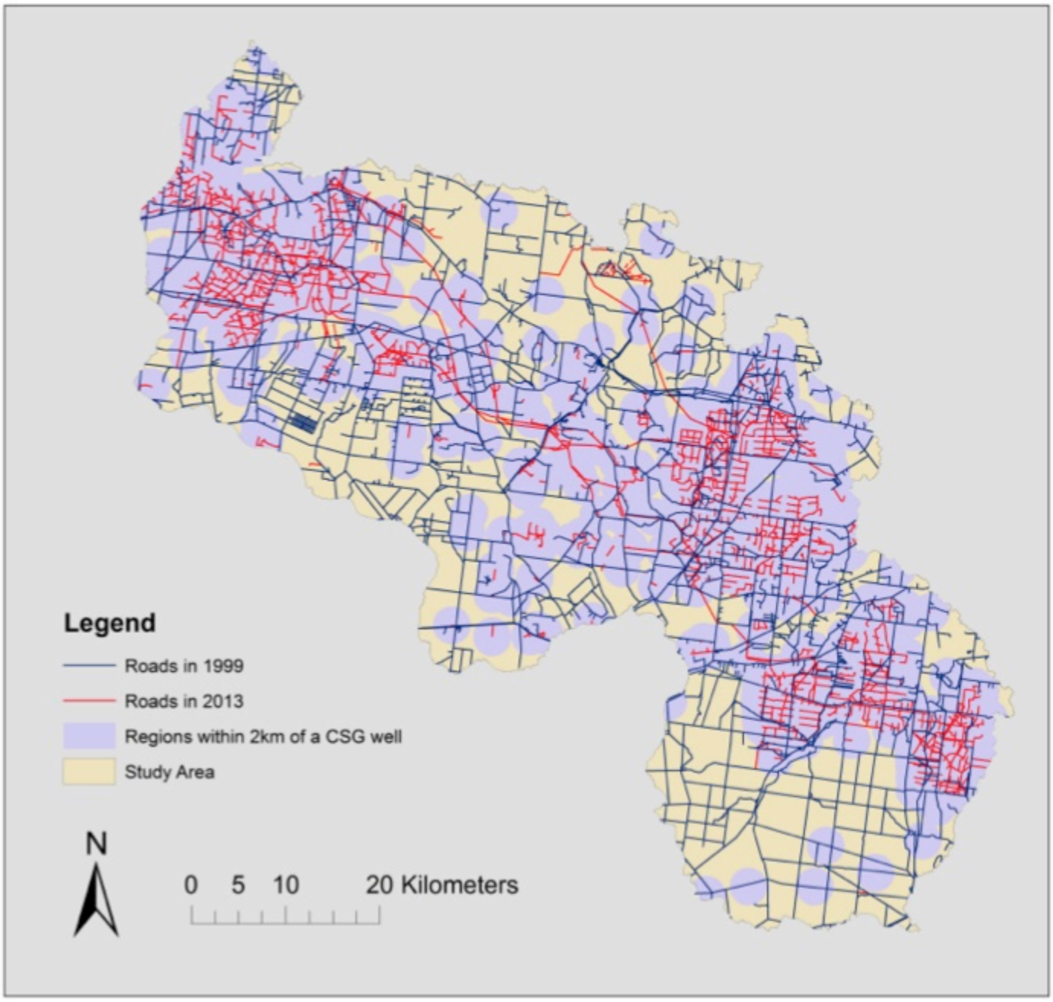

Figure 9: Map of linear infrastructure (labelled as roads) in the study area in 2013, overlaid with roads in the study area in 1999.

4.2 Total Area

The area of vegetated and non-vegetated regions, as classified in the Landsat images in 1999 and in 2013, is displayed in Table 5. This is the change matrix used extensively in the literature (Pontius, Shusas & McEachern 2004). The table shows that afforestation was more dominant than deforestation in the study area during the time period. In terms of net gain, the amount of total area forested increased from 46.47% in 1999 to 51.23% in 2013. The net gain of forest was 18,591.57 ha (4.76%). Swap changes represented 51,844.86 ha or 13.28% of the total region. Table 6 contains data regarding the fragmentation metrics measured. During the period 1999 to 2013, it was found that the number of patches and the amount of forested edge decreased, while the amount of core habitat available increased. Figure 5 is a map of the total study area displaying the spatial location of the pixels in each category in Table 5.

Table 5: Land cover change matrix for the total study area

1999\2013 (*pixels*/**ha**/%)	No woody vegetation land cover	Woody vegetation land cover	Total 1999
No woody-vegetation land cover	*1,826,583*	*494,600*	*2,321,183*
	164,392.47	**44,514.00**	**208,906.47**
	42.13	11.41	53.53
Woody-vegetation land cover	*288,027*	*1,726,757*	*2,014,784*
	25,922.43	**155,408.13**	**181330.56**
	6.64	39.82	46.47
Total 2013	*2,114,610*	*2,221,357*	*4,335,967*
	190,314.90	**199,922.13**	**390,237.03**
	48.77	51.23	

Table 6: Fragmentation metrics for the total study area

Metric	**1999**	**2013**
Number of forested patches	17,870	13,484
Mean patch area (ha)	10.15	14.83
CV mean patch area	8,452.26	6,389.17
Edge density (m/ha)	64.64	50.74
Total Core Area (ha)	78,821.64	108,183.96
Number of disjunct core areas	4,015	3,510
Shape Index	1.23	1.24
CV Shape Index	77.59	65.91
Mean Euclidean nearest-neighbour distance (m)	82.01	93.23
CV Euclidean nearest-neighbour distance	1.86	3.84

4.3 CSG Hotspot Areas

For the purposes of comparison, land cover change was determined within parts of the study area where petroleum leases had been approved in 2012. Land cover change data are summarised in the change matrix in Table 7. While approved petroleum lease areas predominantly cover cleared parts of the study area, net afforestation was also observed in these regions. The amount of land covered by woody vegetation increased from 42.70% in 1999 to 45.57% in 2013 (difference of 2.87%). Swap changes represented 34,589.34 ha (14.06%) of the region. For the inverse – areas outside Granted Petroleum Leases – the net increase in woody vegetation was 11,532.7 ha (7.99% of the land outside granted petroleum leases). Here swap changes represented 11.96% of the area (17,255.52 ha). Landscape metrics for areas within granted petroleum leases are summarised in Table 8. As in the total study area, it was found that the number of patches and the amount of edge forested decreased, while the amount of core habitat available increased.

Table 7: Land cover change matrix for land under granted petroleum leases within the study area in 2012

1999\2013 (*pixels*/**ha**/%)	No woody vegetation land cover	Woody vegetation land cover	Total 1999
No woody-vegetation land cover	*1,295,512*	*270,589*	1,566,101
	116,596.00	**24,353.00**	**140,949.09**
	47.40	9.90	57.30
Woody-vegetation land cover	*192,190*	*974,683*	*1,166,873*
	17,297.10	**87,721.47**	**105,018.57**
	7.03	35.66	42.70
Total 2013	*1,487,702*	*1,245,272*	*2,732,974*
	133,893.00	**112,074.00**	**1,357,343**
	54.44	45.56	

Table 8: Fragmentation metrics for areas under granted petroleum leases within the study area in 2012

Metric	**1999**	**2013**
Number of forested patches	11,102	9,193
Mean patch area (ha)	9.46	12.19
CV mean patch area	6,557.52	3,479.32
Edge density (m/ha)	59.45	51.28
Total Core Area (ha)	45,914.31	54,332.01
Number of disjunct core areas	2,403	2,360
Shape Index	1.25	1.26
CV Shape Index	73.26	63.65
Mean Euclidean nearest-neighbour distance (m)	85.12	94.96
CV Euclidean nearest-neighbour distance	60,180.28	19,765.11

Table 9 is the land cover matrix for land with 2km of a CSG well. As in the total study area in regions under granted petroleum leases, afforestation is the dominant process within 2km of a CSG well. A higher proportion of land near CSG well has been previously cleared than in total across the region, but forest cover increased between 1999 and 2013 by 9486.99 ha (3.95% of land). Swap changes represented 33,556.14 ha, or 13.96%, of land within 2km of a CSG well. For the inverse, forested land cover increased by 6.08% of the area more than 2km from a well (9,104.58 ha) and swap changes accounted for 12.20% (18,288.72 ha) of that area. Table 10 is a summary of the landscape metrics within 2km of CSG wells in the study area. Once again, the degree of fragmentation was observed to decrease in each of the fragmentation metrics of the time period.

Table 9: Land cover change matrix for parts of the study area within 2km of a CSG well and within the study area.

1999\2013 (*pixels*/**ha**/%)	No woody vegetation land cover	Woody vegetation land cover	Total 1999
No woody-vegetation land cover	*1,168,452*	*291,834*	*1,460,286*
	105,161	**26,265.06**	**131,425.74**
	43.74	10.93	54.67
Woody-vegetation land cover	*186,423*	*1,024,402*	*1,210,825*
	16,778.07	**92,196.18**	**108,974.25**
	6.98	38.35	45.33
Total 2013	*1 354 875*	*1 316 236*	*2 671 111*
	121,939	**118,461.24**	**240,400.24**
	50.72	49.28	

Table 10: Fragmentation metrics for parts of the study area within 2km of a CSG well and within the study area

Metric	1999	2013
Number of forested patches	11,468	8,653
Mean patch area (ha)	9.50	13.69
CV mean patch area	*3,325.48*	*2,318.41*
Edge density (m/ha)	64.56	51.56
Total Core Area (ha)	44,567.64	58,331.16
Number of disjunct core areas	2,728	2,451
Shape Index	1.27	1.28
CV Shape Index	*75.54*	*64.06*
Mean Euclidean Nearest-neighbour distance (m)	82.20	94.55
CV Euclidean Nearest-neighbour distance	*17,960.58*	*11,344.84*

4.4 Well-Defined Linear Infrastructure

When raster cells that coincided with roads were all forced to display as cleared cells, the amount of forested land decreased from 181,330.56 to 176,816.88 ha (4,513.68 ha difference) on the 1999 image, and from 199,922.13 ha to 193,902.75 (6,019.38 ha difference) on the 2013 image. The focus of analysis on these images was the fragmentation metrics, which were recalculated. Table 11 displays the fragmentation metrics for the total study area, Table 12 displays the metrics for areas under GPLs and Table 13 displays metrics for areas within 2km of a gas well. As in the images without redefined linear infrastructure, the fragmentation metrics were observed to improve over the study period.

Table 11: Fragmentation metrics for the total study area, with cells through which linear infrastructure passes designated as "cleared"

Metric	1999	2013
Number of forested patches	19,903	16,222
Mean patch area (ha)	8.8839	11.9531
CV mean patch area	927.0376	757.0486
Edge Density (m/ha)	67.90	55.32
Total Core Area (ha)	71,137.17	96,888.87
Number of disjunct core areas	4,759	4,012
Shape Index	1.3223	1.317
CV Shape Index	68.2284	53.9425
Mean Euclidean nearest-neighbour distance (m)	80.0855	88.4143
CV Euclidean nearest-neighbour distance	1,835.134	1,487.3989

Table 12: Fragmentation metrics for the areas under granted petroleum leases in 2012, with cells through which roads run designated as "cleared"

Metric	1999	2013
Number of forested patches	12 404	11 126
Mean patch area (ha)	8.25	9.73
CV mean patch area	921.27	687.12
Edge density (m/ha)	62.44	55.22
Total Core Area (ha)	41,505.48	48,471.84
Number of disjunct core areas	2 730	2 599
Shape Index	1.32	1.32
CV Shape Index	64.28	50.21
Mean Euclidean nearest-neighbour distance (m)	82.78	89.59
CV Euclidean nearest-neighbour distance	1,669.11	948.25

Table 13: Fragmentation metrics for the areas within 2km of a CSG well, with cells through which roads run designated as "cleared"

Metric	1999	2013
Number of forested patches	12,831	10,648
Mean patch area (ha)	8.28	10.76
CV mean patch area	812.85	612.60
Edge density (m/ha)	67.60	55.80
Total Core Area (ha)	40,232.43	52,256.43
Number of disjunct core areas	3,016	2,662
Shape Index	1.34	1.33
CV Shape Index	65.67	50.75
Mean Euclidean nearest-neighbour distance (m)	80.21	88.50
CV Euclidean nearest-neighbour distance	1,344.86	817.06

5 Discussion

5.1 Introduction

The results of the study are discussed in relation to one another and the findings of other similar studies in the literature. It is found that the trends in the study area do not generally correlate with those predicted by other studies of oil and gas development. The landscape fragmentation metrics indicated a decrease in fragmentation, contrary to the findings of other landscape-scale studies of oil and gas development. Similarly, the total area of forested cover increased during the study period, despite the need for clearing for well infrastructure.

5.2 Extent of Land Cover Change

Afforestation was the dominant process in the study area between 1999 and 2013. Figure 10 indicates that net increases in forest cover occurred in all regions tested despite clearing for well pads and infrastructure. The net rate of afforestation was 40% lower within GPL zones than in the total study area and 17% lower within 2km of a CSG well than within the total study area. Also, within these hotspot regions gross gain was much lower and gross loss was slightly higher than in the total study area. Observing the difference in gross loss between hotspot regions and the total study area, and assuming loss due to activities other than CSG development is even across the landscape, CSG activity could only account for gross loss of cover on a very small area of land within hotspot regions. These results suggest that on a landscape scale in this study region, land clearing due to CSG activity has a small but appreciable impact on land cover change, opposite to the dominant processes driving land cover change in the study area.

Swap changes were observed to be lower within hotspot regions than in the total study area (11.8% and 12.2% for hotspot region and 13.3% for the total study area). Lower swap changes are indicative of greater persistence, though in this case, analysis of gross loss and gross gain independently indicates that losses of vegetation are still greater within hotspot zones but not as heavily masked by gains elsewhere as in the total study area. The lower swap changes (and lower net gain) were due to lower levels of gross gain, rather than significantly higher levels of gross loss in the hotspot regions. This may indicate a suppression of regrowth within CSG hotspot regions. It is also important to note that approximately 63% of CSG wells were built on land classified as open in the 1999 image (with some other wells built close to forested cover). While clearing is necessary for the construction of wells in forested cover, deforestation would not be expected for most of the wells.

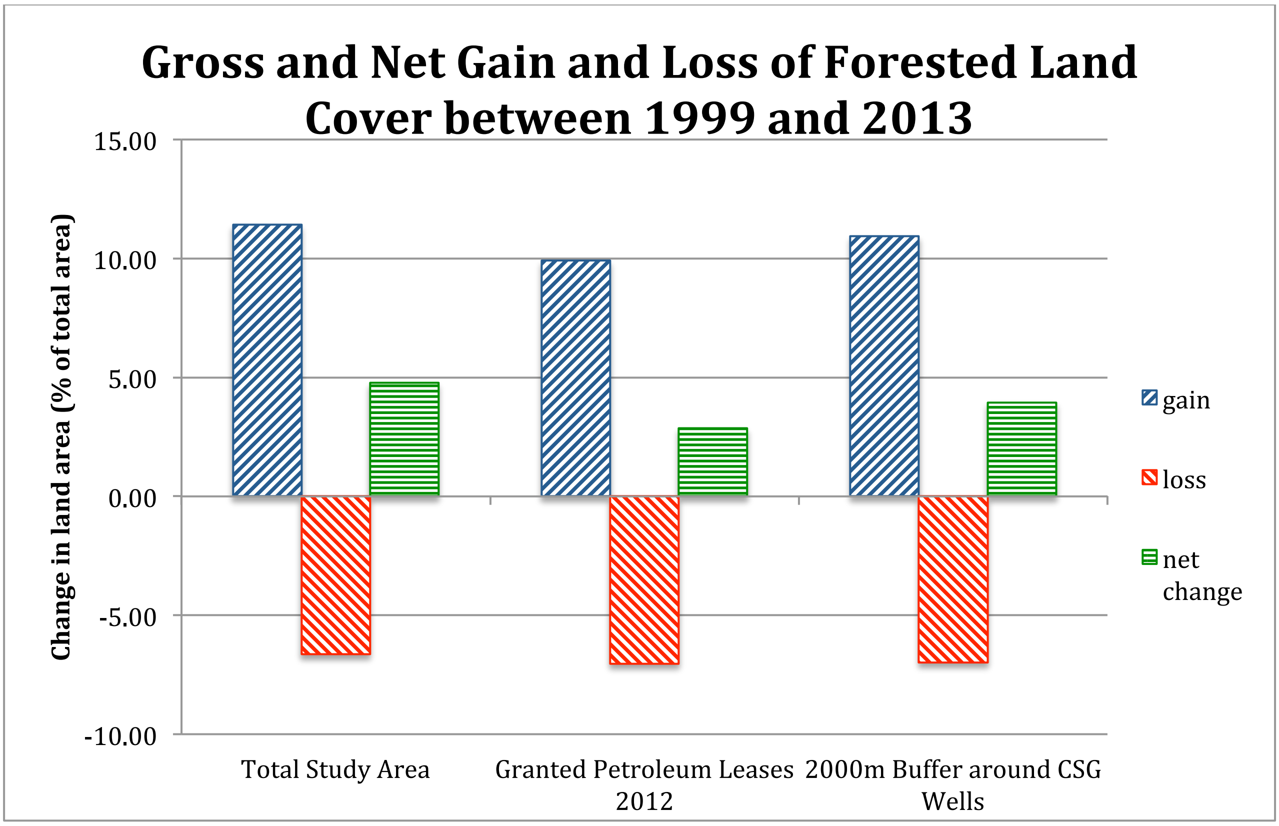

Figure 10: Graphical representation of the gross and net gain and loss of vegetated land cover between 1999 and 2013

The analysis of the images with well-defined infrastructure focused on the effects of vegetation fragmentation, however, the impact of the change on the total land cover area is tested. When roads were defined as occurring on cells classified as open, change in the calculated extent of change is small. Deforestation between 1999 and 2013 in the total study area by roads that were not well defined on the unaltered image accounted for 0.4% of the total study area. This small change will have a minimal impact on the land cover metrics and may indicate that misclassification due to the low resolution of the images in comparison to the size of the infrastructure also has a minimal impact on the final outcome.

Other studies have found that the impact of oil and gas activity on land cover change in a total landscape is small, and therefore a small effect was expected in this study. A study of hypothetical shale development in Canada (260 ha/well pad, 38% forest cover), and a similar study in Pennsylvania (750 ha/well pad, 60% forest cover), both predicted a loss of less than 1% of all forest areas (Johnson 2010; Racicot et al. 2014). Similarly, in Wyoming, a landscape under heavy conventional oil development was found to have a land cover loss of 0.97% (Finn & Knick 2011). The study area under present scrutiny is only 2.22% of the size of the study area in Wyoming, but contains 4.63% the number of wells and 6.15% the road length (i.e. approximately 2 times the well density and almost 3 times the road density).

Despite the similar or greater well pad density in this study area compared to others in the literature, the total land cover change in this study area was strongly positive. The small losses of forest due to CSG development in this study area was masked by other causes of land cover change. The rate of vegetation loss inside hotspot areas above the rate outside the hotspot area (less than 0.01%) is much smaller than that suggested by other similar studies. However, the overall trend of oil and gas development causing a small amount of vegetation loss at a landscape scale is consistent among this study and other in the literature.

5.3 Land cover fragmentation

5.3.1 Number of Patches

The number of patches decreased over the time period of the study in all tests, despite an increase in well pad density. This trend is illustrated in Figure 11. Decreases in the number of patches normally indicate improved landscape health. The rate of decrease in the number of patches was generally found to be lower within the GPL zones than in the total study area (17% and 25% decrease respectively for the unaltered images and 10% and 18% decrease respectively for the images with well defined roads). While this may indicate that there is some effect of CSG activity on isolating vegetation, the effect is not observed to the same degree within the 2km buffer zones (25% in the unaltered images and 17% in the images with well-defined linear infrastructure).

Although Bi, Wang and Lu (2011) found a strong correlation between well pad density and an increased number of patches, this study does not support that finding. Similarly, a hypothetical shale gas development in Canada was found to increase the number of forest patches in a study area by between 13% and 21%, assuming well pad density of one well per 260 ha (roughly equivalent to the density in the total study area in this study) (Racicot et al. 2014). Differences in the nature and aims of these studies may partially explain the different result. Regardless, it indicates that processes occurring at a small scale do not necessarily correspond to those occurring at a larger scale.

In this study, the increase in well pad density was slightly greater in 2km buffer zones than in GPL zones. The density increased from no wells to a density of 153.9 ha/well and 157.5 ha/well respectively. However, this difference in well density cannot explain the very large differences in the change of the number of patches between the hotspot region definitions. When CSG infrastructure was well defined, the impact on the number of patches measured is appreciably higher, indicating that, to some degree, CSG infrastructure does increase the number of patches in a region.

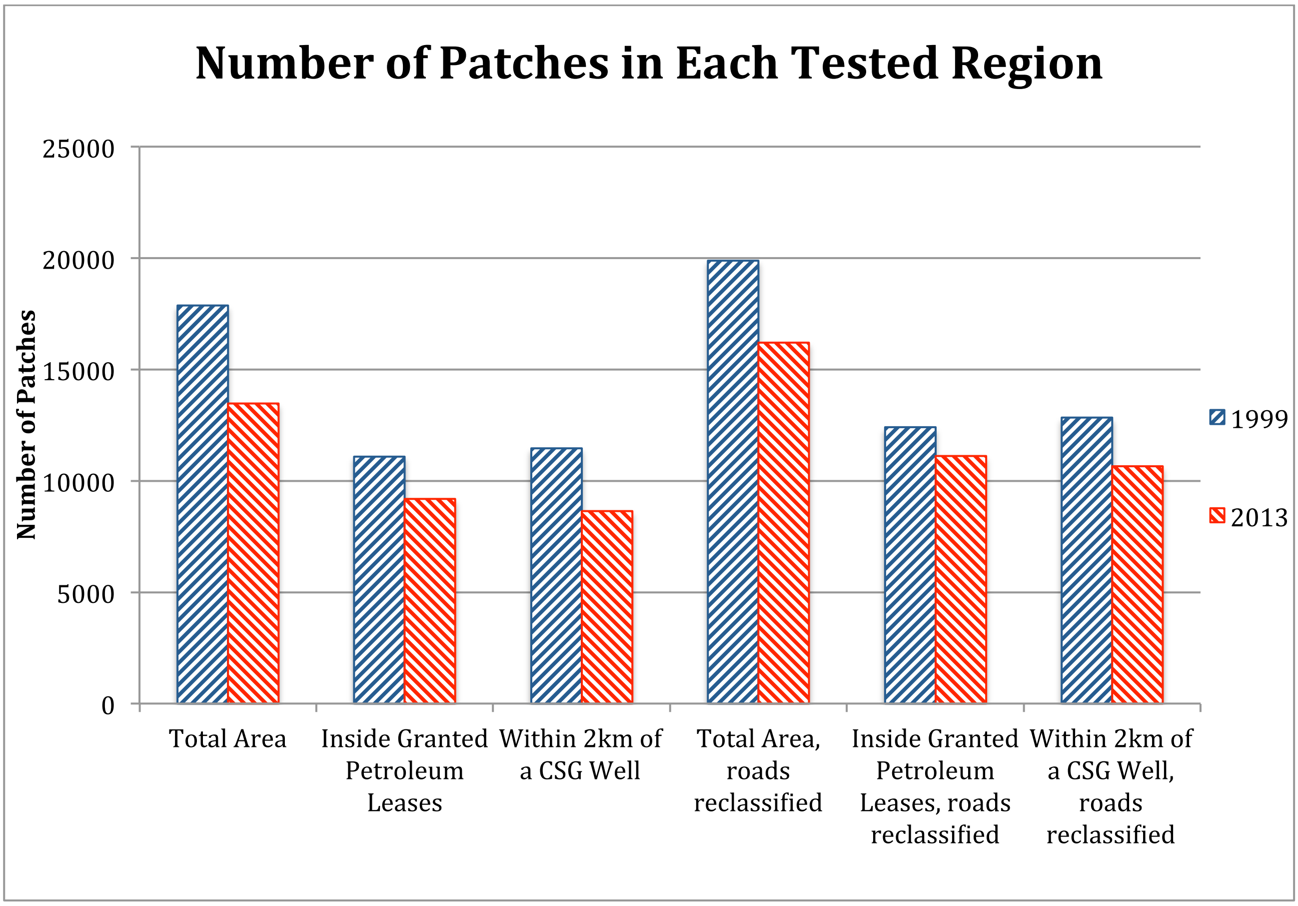

Figure 11: Number of patches in each tested region

5.3.2 Patch Area

Mean patch area was observed to rise in all regions tested. This result is illustrated in Figure 12. Increasing patch area indicates that the reduced number of patches (section 5.3.1) were, on average, of more ecological value in 2013 than in 1999. Patch size was generally lower in hotspot regions, and increased at a lower rate. While a smaller rate of increase may be attributable to CSG activity, it is not clear why there was a bias towards drilling of CSG wells near small patches of vegetation, and whether that dynamic has been the major cause of the lower growth in patch size. Regions such as the large production forestry area (Kumbarilla State Forest) in the south-east of the study area, and the rural residential subdivision in the south-west, are not within dense CSG production regions and are likely to display significantly different landscape dynamics. In the classified image with well-defined linear infrastructure, patch size was also smaller, and increased at a lower rate, than the corresponding regions without alteration. However, the general pattern of change was similar, with little new relevant information in the context of this study.

The statistical distribution of patch sizes in the landscape changed considerably in over the study period, and was different in hotspot areas compared to the total study area. This analysis was achieved by measuring the coefficient of variation of patch area, as displayed in Figure 13. During the study period, distribution of patch area around the mean tended to become smaller, reducing landscape diversity. Similarly, diversity of patch sizes was found to be low in hotspot areas, and generally decrease at a greater rate during the study period (except with 2km buffer zones in the unaltered image). The distribution of patch sizes was very much more homogenous when roads were well defined, indicating that narrow clearings that did not completely isolate patches in the unaltered image tended to divide larger patches into patches of more or less equal areas. Together, these results indicate that development of linear infrastructure in the study area, particularly due CSG activities, tended to create patches of regular size. While this size has increased overall, the lower diversity potentially impacts species that rely on particularly large or small patches.

Other studies found that patch size was negatively impacted by oil and gas development. While average vegetation patches were considerably larger in a study in Canada, a decrease of 10% to 15% was expected due to shale gas development (Racicot et al. 2014). Oil production in Wyoming between 1900 and 2009 was observed to reduce patch sizes by 45% within 0.2km of a well, but only approximately 10% across the landscape (Finn & Knick 2011). The authors considered this change to be small. Well density in this study was double, and road density was triple, that of the Wyoming study. Despite less favourable conditions in the study area in southern Queensland than in other regions studied in the literature, the increase in patch area indicates an improvement in landscape health.

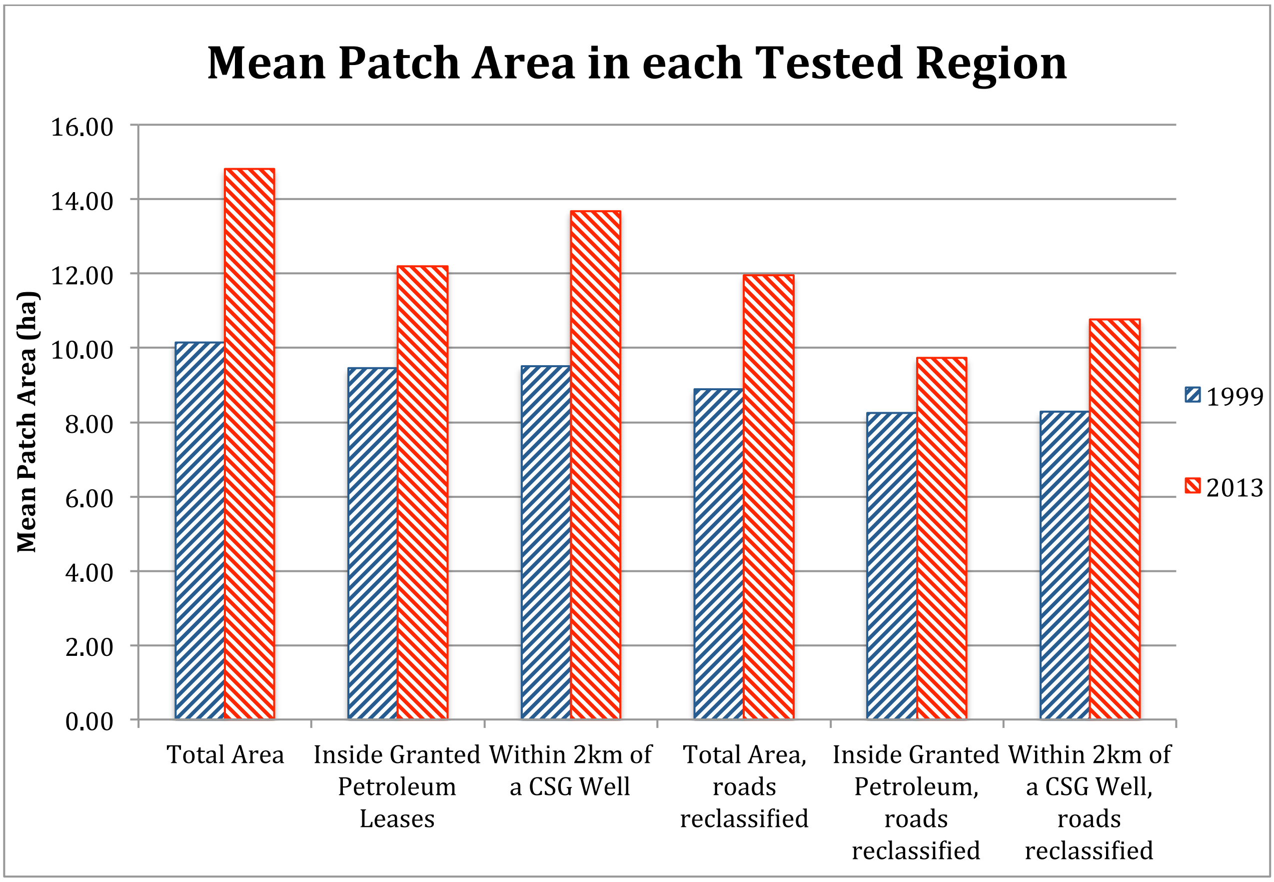

Figure 12: Mean patch area in each tested region

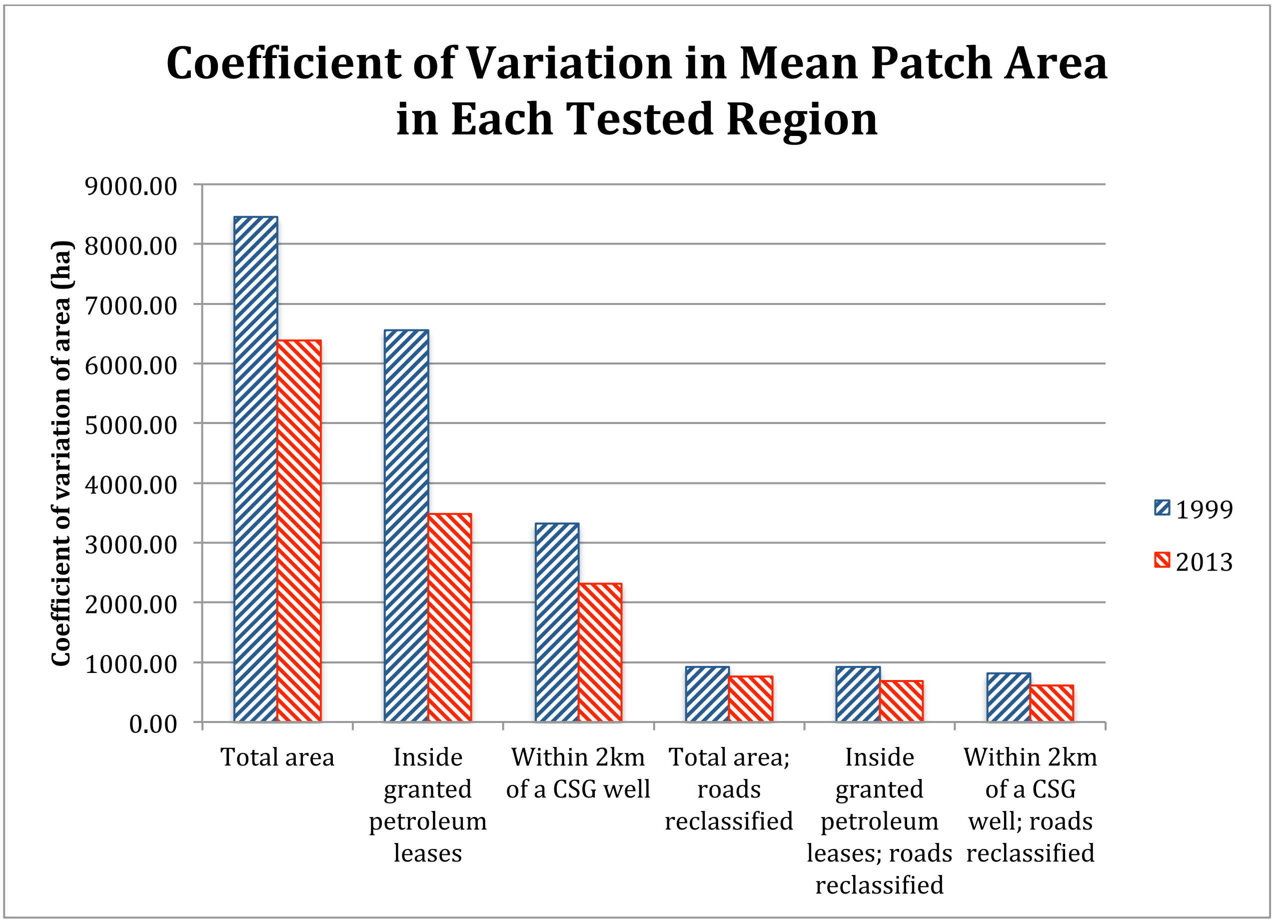

Figure 13: Coefficient of variation in mean patch area in each tested region

5.3.3 Edge Density

Edge density changed considerably during the study period. Edge density was observed to decrease between 1999 and 2013 in all areas tested (14% decrease in GPL zones, 20% decrease within 2km of a CSG well, 22% decrease in total study area), as shown in Figure 14. The edge density within 2km of all CSG wells was similar to the density throughout the study area. Edge density was reduced at a lower rate in GPL zones than in the total study area or within 2km of a CSG well. The mixed results mean that the impact of CSG is uncertain. As is the case with each of the metrics, edge density was significantly different within GPL zones compared to the total study are, even before the commencement of CSG development, and may be affected by that initial bias. The images with well-defined roads contained slightly higher edge densities, but the effect was minimal and did not change the general patterns of change or relationship between different areas tested to a large degree.

Edge density was found to increase in other studies, in contradiction to the findings of this study. Within the total landscape in parts of Wyoming, edge length increased by approximately 8%. This was considered to be a small increase (Finn & Knick 2011). The opposite effect has been observed despite the fact that the Condamine catchment is contained double the well density and triple the road density than that of the Wyoming area of study. In Washington and Bradford counties, Pennsylvania, the drilling of CSG and shale wells caused smaller increases in edge density. A 2.3% increase in edge density was observed in a county with well density was more than 1310 ha/well (5 times lower than in this study area) and a 4.8% increase in edge density with a well density of 332 ha/well (more dense than in the current study area) (Slonecker et al. 2012).

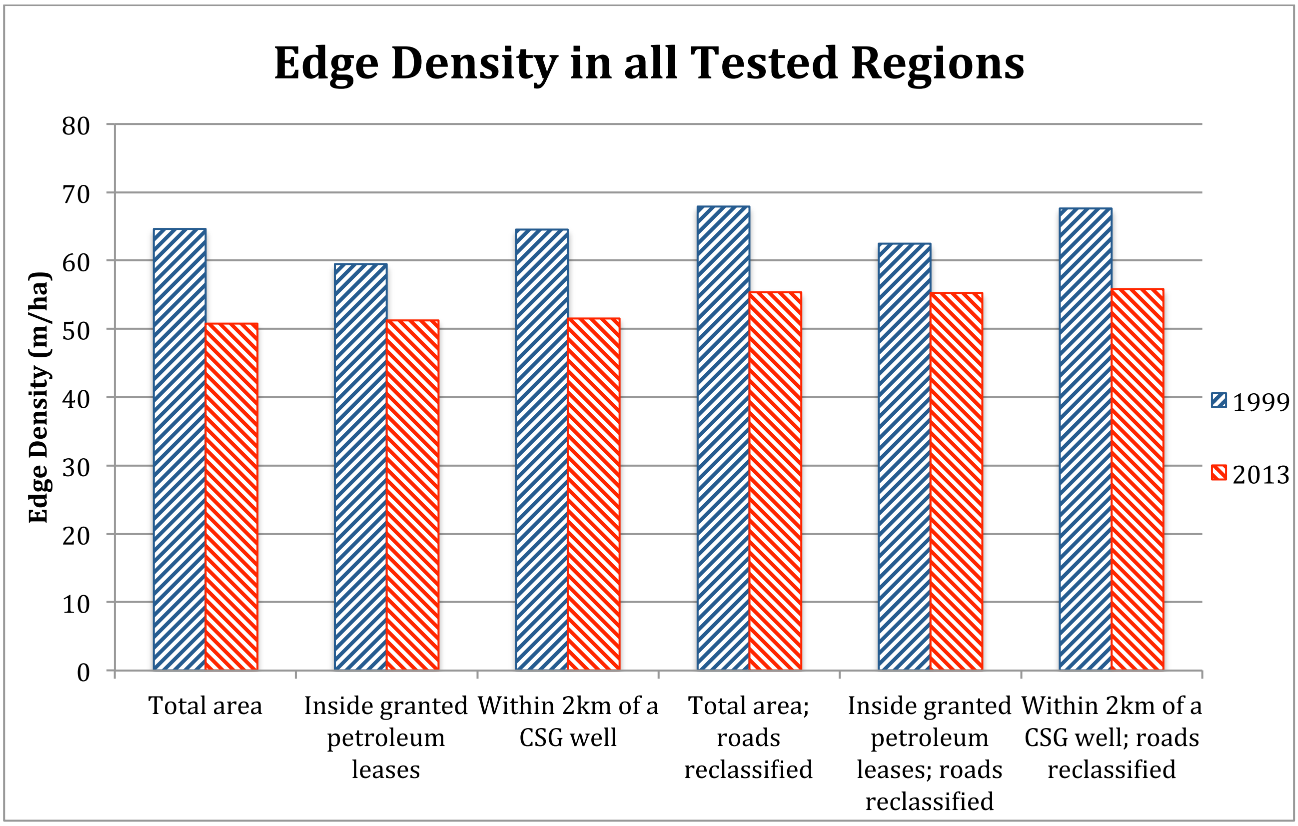

Figure 14: Edge density in all tested regions

5.3.4 Total Core Area

Total core area was observed to rise in the total landscape as well as in the hotspot regions. This indicates that in 2013, the landscape was better suited to core-obligate species than prior to intense CSG development in 1999. This is generally a marker of a more healthy environmental state. The rise in the total core area corresponds to increases in the patch area between 1999 and 2013 in all tests and small changes in shape index and edge density. Figure 15 displays the core area as a function of total area, called core area density, so that comparisons may be made between the total area and hotspot regions. Core area density was found to be smaller within hotspot zones, which corresponds to the smaller number of patches and lower mean patch areas within those zones. Increases in core area density were much less within these zones.

As in the analysis of total area, it is possible that the dynamics of the small patches within hotspots zones would have behaved differently, even if CSG development had not occurred. However, Figure 16 demonstrates that core area density increased at a slower rate in the images where roads are well defined than in each of the unaltered images. For example, in the total study area, the rate of increase was 37% for the unaltered image and 17% for the image with well-defined roads. However, the difference in rates of change between the altered and unaltered images are not significantly higher in hotpot regions compared to the total study area which might have been expected if CSG development were the major cause of the infrastructure construction that impacted on core area density. Much of the observed reduction in the rate is due to infrastructure development, some of which is CSG infrastructure development.

Previous studies have shown that oil and gas development decreases the amount of core habitat area in a landscape, contrary to the findings of this study. In Wyoming, core areas of shrub land were reduced by ~13% in the total study area using an edge width of 60m (Finn & Knick 2011). Though the well density of the present study is double and road density is triple that of the Wyoming study, the opposite effect was observed. Once again, the nature of this study may provide a partial explanation for the observed difference.

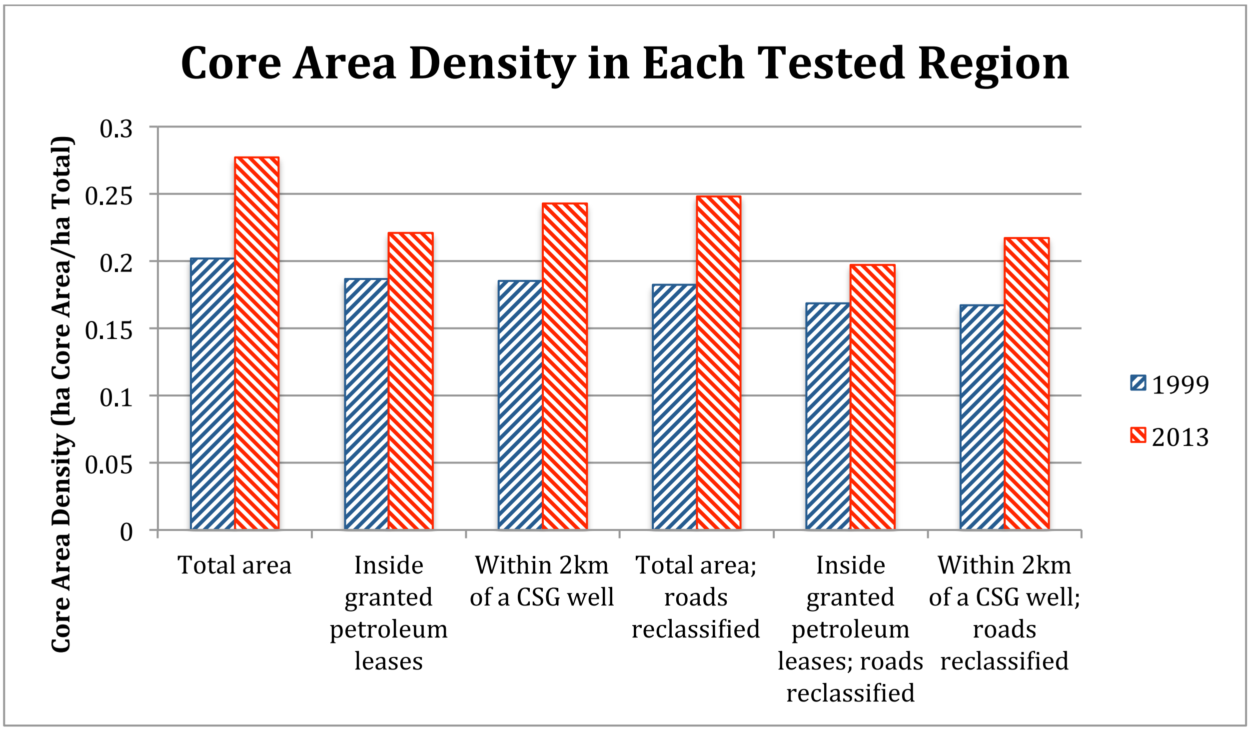

Figure 15: Core area density in each tested region

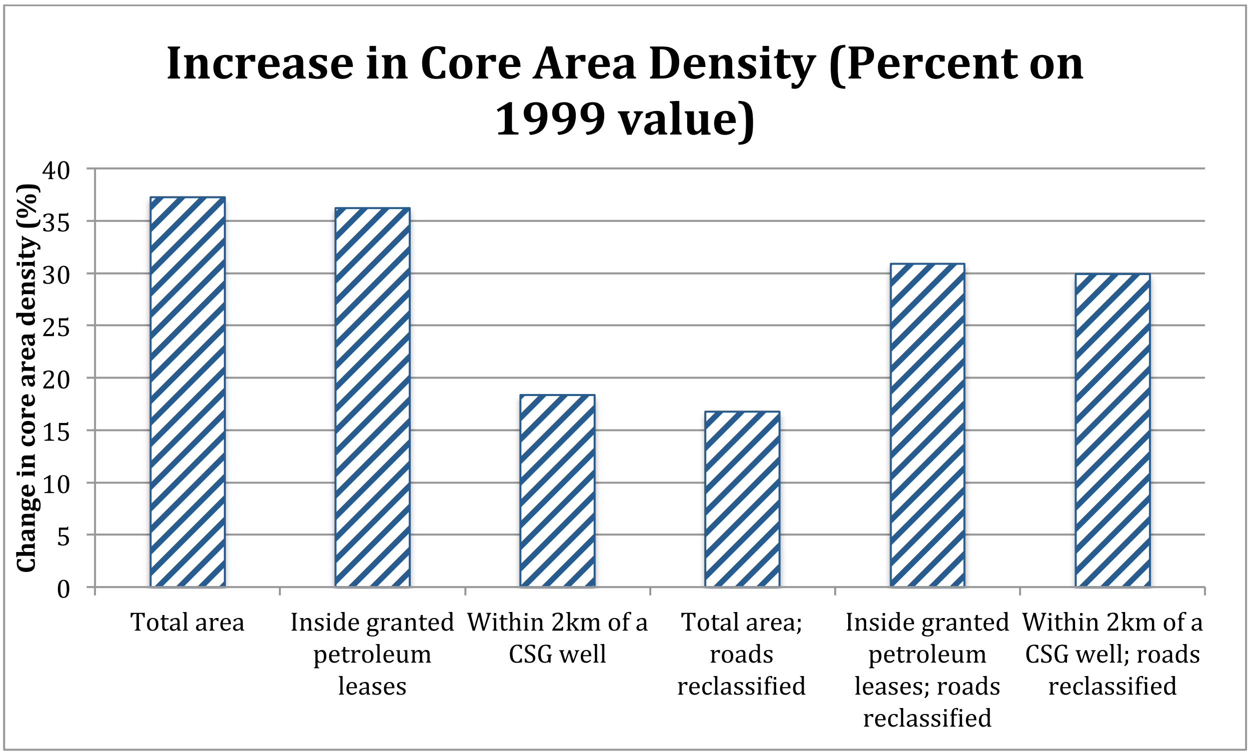

Figure 16: Increase in core area density for each region tested

5.3.5 Number of Disjunct Core Areas

The number of disjunct core areas, displayed as a function of total area (density of disjunct core areas) in Figure 17, decreased in the total study area, and in the hotspot areas. This result reflects an increase in the size of patches, and occurred despite no appreciable change in patch shape being recorded. Each of these disjunct core patch areas is likely to be more ecologically important, given the greater total core area measured. The absolute density of disjunct core areas in the landscape, and rate of decrease (absolutely and proportionately) in the density of patches between 1999 and 2013, was distinctly larger when roads were well defined. Clearly, the linear infrastructure present in 1999 dissected core patches that would have otherwise existed (and did exist in the unaltered image), increasing their number. However, it is more difficult to explain the reduction in the number of core areas corresponding to the large increase in road density between 1999 and 2013. One explanation is that linear infrastructure (particularly that associated with CSG) removed some small patches, and associated core areas, all together.

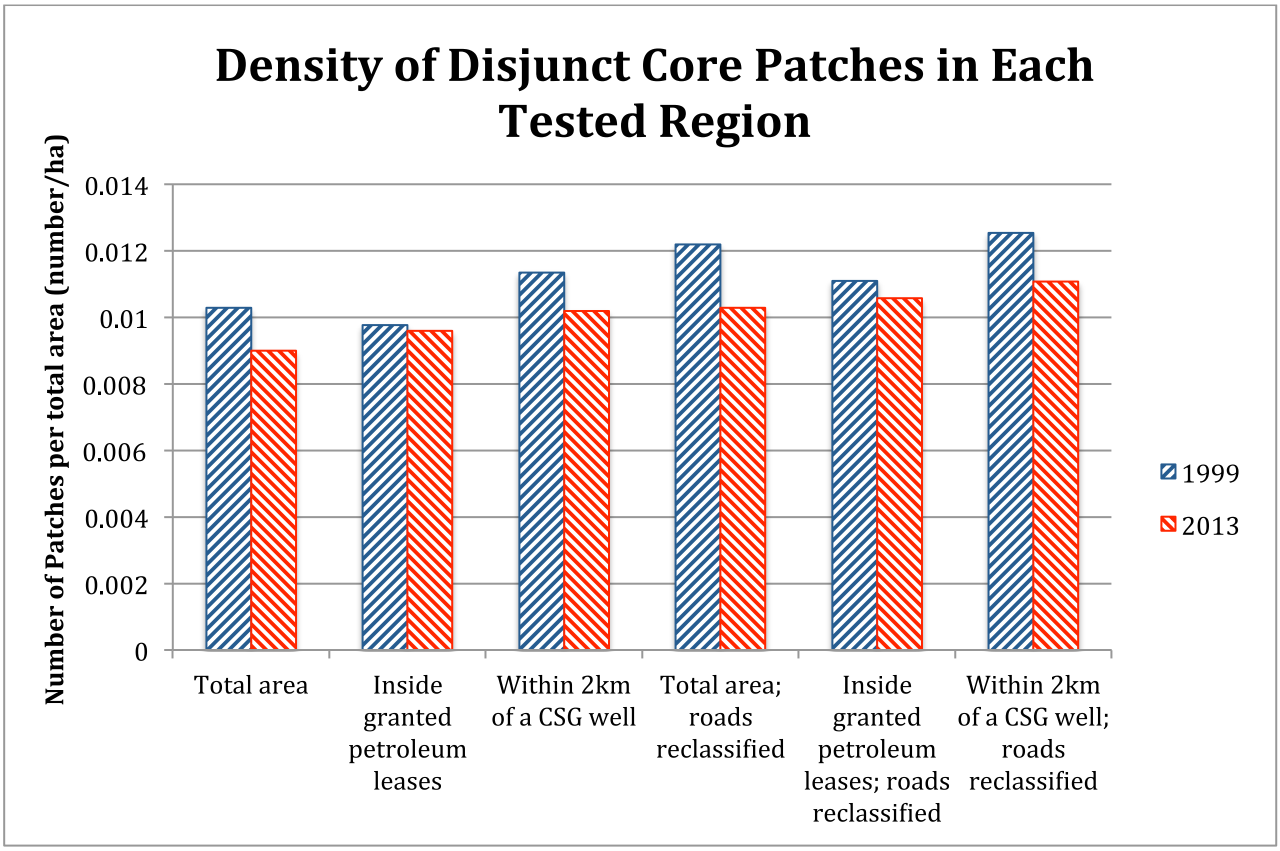

Figure 17: Density of disjunct core areas in each tested region

5.3.6 Shape Index

In the total area, and the hotspot regions, the change in shape index over the study period was minimal, and there was little difference in the rate of change inside and outside buffer regions. These findings are illustrated in Figure 18. While in the unaltered images, shape index increased between 1999 and 2013 to a small degree, after roads were well defined as linear clearings, a small decrease in patch complexity was observed. This decrease correlates with an increase in road length between 1999 and 2013, and indicates a correlation between increasing road density and increasingly regular vegetation patch shape.

Despite a fall in shape index over the study period, images in which the linear infrastructure is reclassified have much greater absolute patch complexity than the corresponding images without reclassification. This result indicates that the transformation to defined roads continuously was important in measuring shape index. Small discontinuities in the clearings for linear infrastructure in the classified images have led to a severe over estimation of patch complexity in the unaltered images. For the analysis of patch shape, the result from the unaltered images should be used with caution.

Bi, Wang and Lu (2011) found that increasing road density was closely correlated to increasing regular shapes of remnant vegetation. The decrease in shape index with over the study period in the images with well-defined roads corresponds to the findings in Bi, Wang and Lu (2011). Finn and Knick (2011) reported the opposite result, i.e. that increased road density corresponded with small increases in patch complexity in the shrub lands of Wyoming. It is possible that the Wyoming study was hampered by the same inaccuracies that impeded the analysis of the unaltered images in this study.

The second-order analysis of shape index revealed conclusive results, and these are shown in Figure 19. The variability of shape complexity is shown to decrease over the time period, and to be clearly affected by the strong definition of roads in the classified images. The results indicate a link between development in the landscape, particularly linear infrastructure associated with CSG development, and a greater regularity of patches across the landscape. While not of direct ecological significance, the finding does demonstrate that infrastructure development in general, and CSG in particular, does have a discernable impact on the landscape structure.

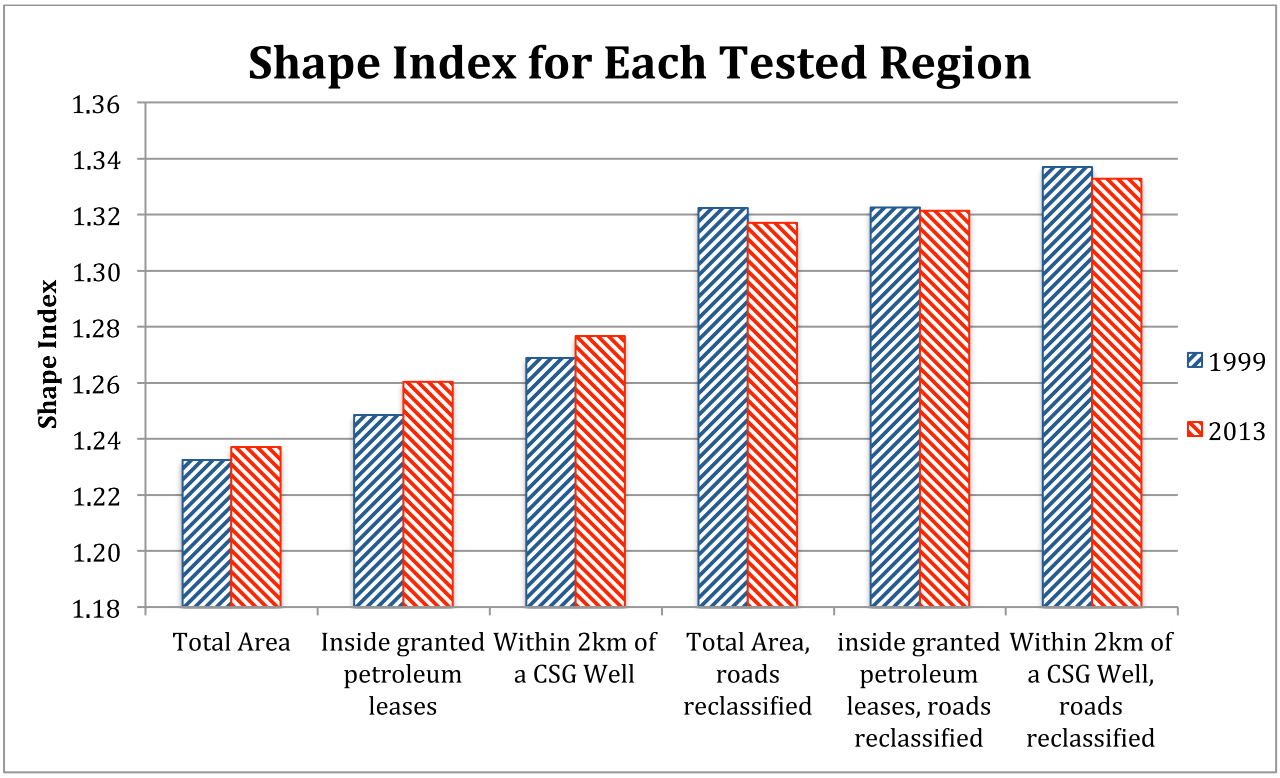

Figure 18: Shape index in each tested region (1999 and 2013).

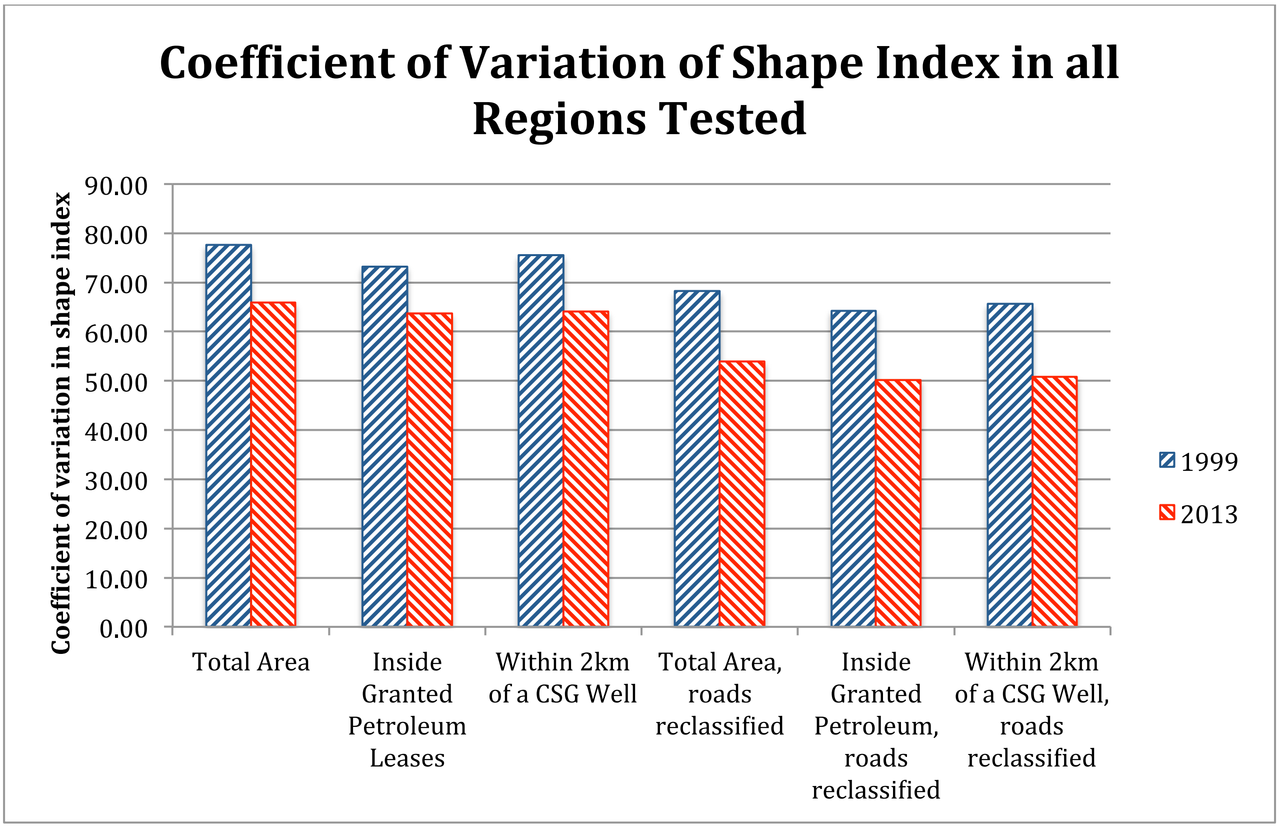

Figure 19: Coefficient of variation of shape index in all regions tested

5.3.7 Euclidean Nearest Neighbour Distance

The Euclidean Nearest Neighbour Distance (ENND), illustrated in Figure 20, was shown to increase to a large degree between 1999 and 2013 in the total landscape and in hotspot areas. While each of the other metrics indicates that the landscape became less fragmented during the study period, individual patches became, on average, more isolated. In the unaltered images, the average ENND increased from between 82.01 and 85.12 metres to between 93.23 and 94.96 metres (depending on whether the total area or hotspot area was analysed). In the images with well-defined roads, the increases were from between 80.09 and 82.78 to between 88.41 and 89.59. In the total study area, there was a 10.4% increase over the study period in the image with well-defined roads, but a 13.7% increase in original image. A similar pattern was observed in hotspot regions. The increase indicates that, while individual patches were better able to accommodate ecological communities, there is a greater chance that populations will be blocked from moving between patches.

The reduced increases in the ENND were lower in the images with well-defined road clearings is not surprising. Clearings for roads and pipelines are not generally wider than one or two pixels (30-60m). The narrow nature of the linear infrastructure constructed in the study area would be expected to reduce the average distance between patches. Infrastructure requiring larger areas, such as well pads, may cause larger areas of vegetation to be lost, but are not as likely to isolate patches from one another as linear infrastructure. Very large clearings for dams have some effect on increasing isolation, as well as creating barriers to movement by land. However, as is the case for the other landscape metrics calculated in the study area, linear infrastructure associated with CSG has the opposite effect on the environment to the other drivers of change. In terms of isolation from hotspot zones, the ENND was shown to be higher in GPL zones than in the study area as a whole, but the isolation within

2km of well pads in the study area was similar to the total study area. This inconsistent pattern of change in hotspot zones makes the results difficult to analyse.

The coefficient of variation of Euclidean nearest neighbour distance around the mean is shown in Figure 21. There is a small increase in the coefficient of variation between 1999 and 2013, signalling greater dispersion. While the mean has increased, this trend is countered by the introduction of a number of small distances between patches caused by the construction of linear infrastructure such as roads. The correlation between road density and the greater variation in the distribution of gap sizes is borne out in the higher absolute coefficient of variation and greater proportional rise in coefficient of variation with time in the images with well-defined roads. While the dominant processes in the landscape have caused an increase in average ENND, other processes, such as the construction of narrow linear infrastructure for CSG activity, has an identifiable impact in the statistics.

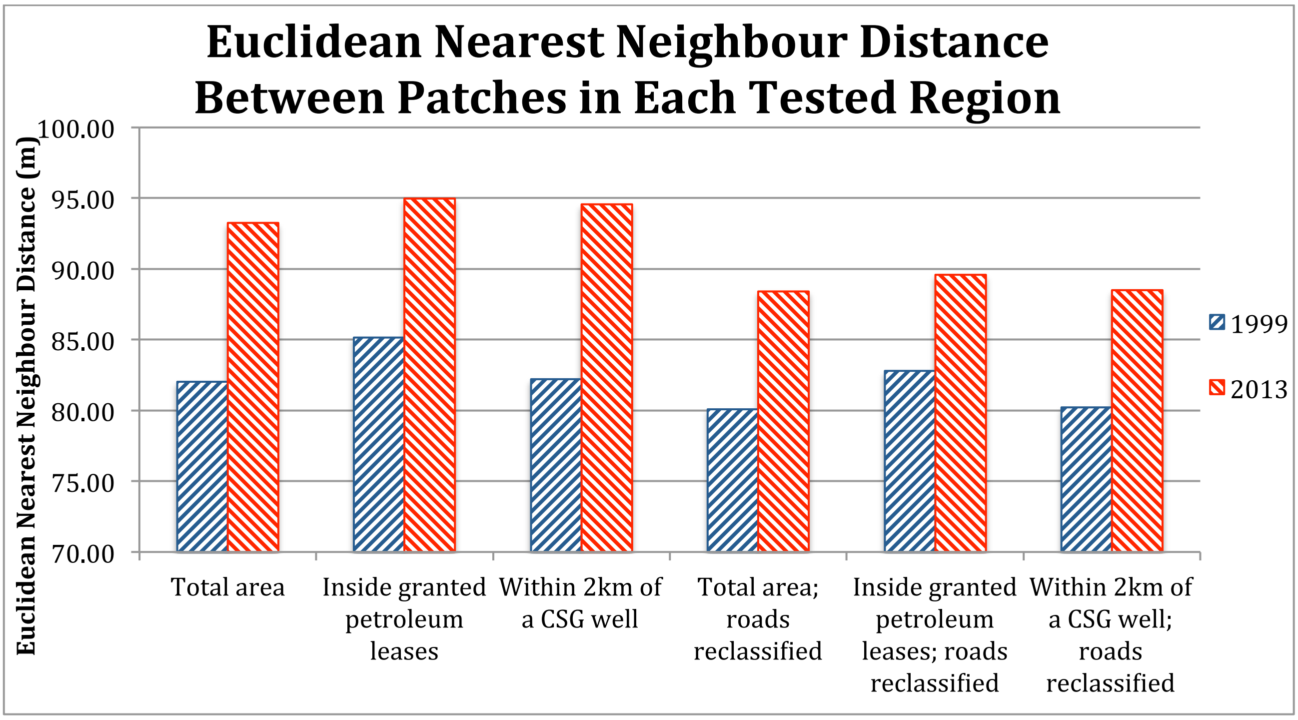

Figure 20: Euclidean nearest neighbour distance in each tested region

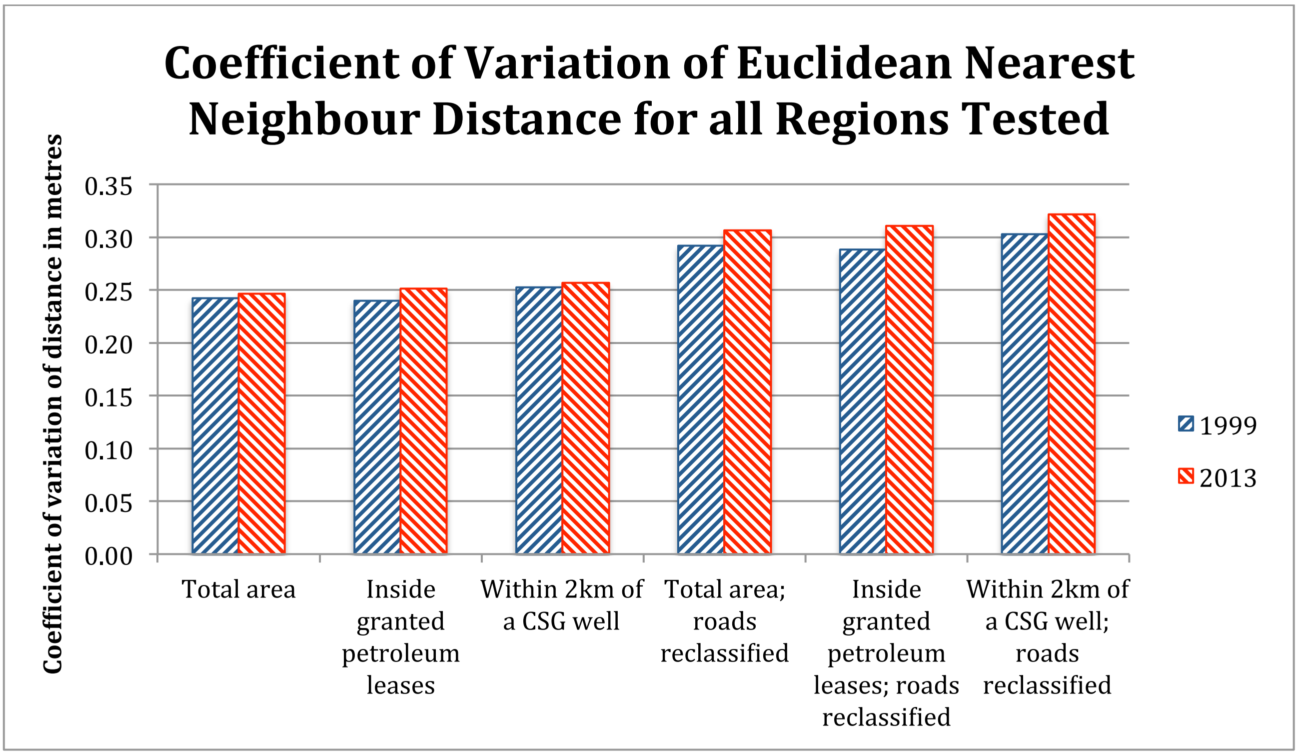

Figure 21: Coefficient of variation in Euclidean nearest neighbour distance for patches in all tested regions

5.4 Accounting for Change

The statistical analysis of change has indicated that the area of vegetated land cover has increased and degree of fragmentation has generally decreased during the 14-year period from 1999 to 2013. However, it is not immediately evident how much of this change may be attributed to CSG activities. Upon visual inspection of Figure 5, and manual comparison with the corresponding satellite images in Figure 2 and Figure 3, some causes for change can be surmised. In this section, major examples of areas of change are classified as likely to be due to CSG, due to unknown processes, or unlikely to be CSG related. Each site-specific example is referenced using longitude and latitude, and marked on the map in Figure 22. It is important to stress that the sites mentioned are examples only, and that this analysis is not intended to be a full survey. The analysis is intended to demonstrate that more than one reason for land cover change exists in the study area, and attempts to validate the conclusions drawn from the statistical analysis. The work focuses on larger areas of change, but smaller disturbances across the landscape can be similarly classified.

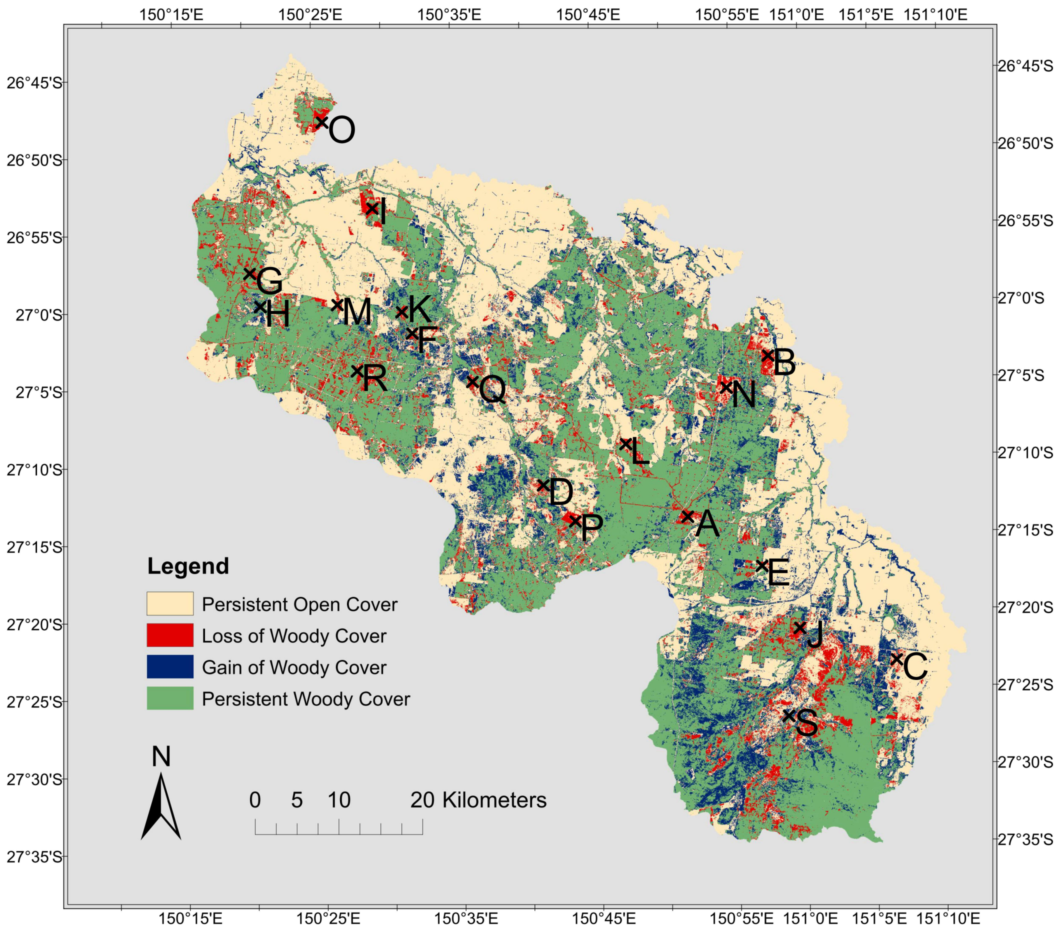

Figure 22: Map showing regions of persistence, gain of woody cover and loss of woody cover, with points of interest included in the discussion

A number of regions of change can be directly related to CSG activity with a high degree of confidence.

- A facility named as a 'pipeline facility' by the QLD Department of Natural Resources and Mines (2014c) has caused a large area of vegetation loss at S 27°13' E 150°52' (site A). Pipelines radiating from this site are also associated with large areas classified as 'vegetation loss' in Figure 5. A number of similar 'pipeline facilities' and other large infrastructure required to support CSG development are planned as part of the QCLNG development (QGC Limited 2009b).

- The expansion of the road network in the study area has been extensive, and mostly associated with CSG development. This has been demonstrated in Figure 9. Linear clearings across the study area are associated with this development.
- At S 27°03’ E 150°58’ (site B), dams have been constructed, accounting for much of the vegetation loss in that patch. Similar development has caused notable changes at S 27°23’ E 151°07’ (Site C), S 27°12’ E 150°41’ (site D) and S 27°17’ E 150°56’ (site E). Other unidentified infrastructure built within well clusters, such as at S 27°02’ E 150°32’ (Site F), may relate to CSG activity. Large areas of regeneration nearby these CSG locations appear to be mainly classification errors (for example at around site E and site F), activities on adjacent land holdings (for example a Paulownia plantation near site E) or the general increase in vegetation along riparian zones (near site A). Dams and other infrastructure that appear to be CSG related have been constructed in other parts of the study area, but largely on previously cleared land.
- Losses west of E 150°24’ (site G) are largely attributable to CSG infrastructure. A CSG industry representative has acknowledged this gas field to be one of the most poorly designed in Queensland (Galilee Basin Operators Forum 2012). Gains of vegetation at S 27°0’ E 150°22’ (site H) appear to be legitimate, and have occurred in close proximity to CSG development, but other similar changes in proximity to CSG development appear to be classification errors.

Some large areas of change are either not CSG related, or their cause is not clear:

- Loss of vegetation has clearly occurred in some areas where new infrastructure was not observed on the cleared site. For example, intense CSG development is occurring around S 26°53' E 150°29' (Site I), S 27°21' E 150°59' (site J), S 27°00' E 150°31' (Site K) S 27°09' E 150°47' (site L) and S 27°00' E 150°26' (Site M), but the full extent of the clearing is not easily attributable to CSG. Despite use of some of the cleared area for roads and well pads, most of the cleared area is not used for constructions, or development that is obviously associated with CSG development. In many cases (for example site I, site J and site K), the extent of the cleared patches match the cadastral survey very closely, indicating that clearing may be occurring due to decisions made by landholders independent of CSG companies. The effect of the CSG industry on the decision to clear in these areas is questionable.
- The loss of vegetation at S 27°05' E 150°55' (site N) is particularly extensive, and in a region heavily impacted by CSG developments. It is not clear whether or not the large patch of cleared land has a connection to CSG activity. The Braemar 2 CSG-fired Power Station occupies the far southern part of the patch of cleared vegetation. The losses due to this construction do not account for the very large losses immediately to the north of the power station, and are offset by nearby regions misclassified as having gained vegetation. One small part of this patch was occupied by infrastructure that may be associated with CSG activity in the 2013 image. This area is misclassified as a 'gain in vegetation'. Power lines radiating from this site have caused some further losses.

In other areas CSG wells are located well away from the site:

- The cleared patches near S 26°47' E 150°26' (site O), S 27°14' E 150°43' (site P), and S 27°05' E 150°36' (site Q) are not in the immediate vicinity of CSG wells, and CSG infrastructure is not visible on each site in the 2013 image. Other processes have driven change in these locations.

- In the region south of S 27°02' and west of E 150°35' (around site R), land holdings are predominantly small. In 2006, much of this region was indicated to be rural residential living or low use land. Very little CSG activity has occurred in this region, but significant losses and gains of land cover have occurred. Much of this activity matches the cadastral boundaries very closely, and tends to indicate that the changes are not CSG related.
- Gains along drainage lines are extensive, and may be caused by improved management of riparian zones.
- In production forestry regions, large swap changes are observed. Areas of gain and loss, particularly south of S 27°25' (around site S) can't be easily attributable to CSG activity, and is more likely forestry activity. There also appears to be significant amounts of classification error in this region.

5.5 Summary

The overall process is one of afforestation and reduction in fragmentation, despite the influence of CSG development. The number of patches fell over the study period. However on average, these patches were larger, and the overall forest cover was higher in 2013 compared to 1999. This was accompanied by a reduction in edge density but little change to the shape index. A possible pattern of change to explain these findings is one of a loss of very small patches by merging remnant stands with bridges of regrowth. If patches nearer one another were bridged preferentially, such a hypothesis would also account for an increase in the average distance between patches, and an increased total core area with an associated decrease in the number of disjunct core areas. While the CSG activity is observed to cause deforestation and impact on the integrity of core forest areas, it does not have a large enough effect on the landscape to compensate for the effects of more dominant drivers of change.

Although the coefficient of variation of patch size and patch shape are orders of magnitude higher than the values themselves and therefore have not been displayed on the charts), the analysis is still reliable because the landscape is compared to itself. The coefficients of variation of patch size and patch shape show that the developments that have been occurring in the landscape, including CSG developments, create greater homogeneity in the landscape. While the implications are difficult to define for the general case, it means that there is less diversity in patch types, and the possibility of impacts on species that rely on patches at either extreme of the diversity spectrum. The coefficient of variation of Euclidean nearest neighbour distance was observed to show greater dispersion across the landscape in 2013 than in 1999. While the major processes of change have increased the mean ENND in the landscape, the processes that create fragmentation with more narrow clearings have also been significant enough to be registered in the statistics.

Consistently, in each of the aspects of the landscape measured, the 2km buffer zone resembled the total landscape more closely that the GPL resembled to total landscape. The major differences between the GPL and the 2km buffer zone are not easily explained, nor can one or the other be dismissed as obviously providing erroneous results. While the GPL is not tightly defined around CSG developments, where those developments occur near the boundary of the GPL, it provides a stronger definition than the 2km buffer. However, it has not included some of the most significant CSG infrastructure in this study such as some holding dams, parts of linear features (pipelines and power lines), and isolated exploration wells. While the 2km buffer zones do take better account of infrastructure close to wells, such as dams, it is potentially biased by other activities that occur around isolated exploration wells. In particular, some of the changes occurring in the south of the study area on subdivisions of rural residentially zoned land and in production forestry are included in the 2km hotspot regions, but not GPL regions. The large forest area in Kumbarilla State Forest has a different dynamic to the rest of the study area and may bias the results from the total study area, and partially from the 2km buffer zones.

The differences observed between the results in this study and those in the literature are likely to have to do with the nature of the studies. This is a longitudinal study of total changes in the landscape over a fourteen year period, while many of the other studies that have been used for comparison are predictive, and therefore only consider changes due to oil and gas activity. Other drivers of change are discounted, and the landscape around the oil and gas activity is assumed to be static. Each approach has its merits, but the advantage of this study is that the relative role of CSG in causing landscape change may be analysed.

6 Conclusion

6.1 Conclusions

There is no doubt that significant change has occurred in the patterns of land cover in the study area during the period 1999 to 2013, that CSG developments have been pursued extensively in the landscape and that CSG developments have led to clearing of vegetation. However, a link between small-scale vegetation loss and the increase in landscape-scale vegetation fragmentation has not been demonstrated in this study. Similarly, at a landscape scale, overall losses of vegetation were not observed. The study indicates that, despite extensive CSG activity, the vegetation in the landscape was less fragmented in 2013 than in 1999.

By visual examination, some landscape clearing is easily attributable to CSG activity, and a proportion of this activity has impacted on core forest areas. However, this study shows that there are other drivers of land cover change and fragmentation in the study area. Unlike other similar studies, this work does not attempt to filter the changes due to other activities out of the measurements of landscape change. Some of the activities that have caused change are forestry (in native forests and plantations), agriculture and rural residential living with large areas of land under low intensity use. The causes of many of the changes are not easily identifiable on the satellite imagery. The statistical analysis of change indicates that these activities have a more significant impact on land cover change and fragmentation than CSG.

6.2 Recommendations for Practical Application

The research provides an insight into the magnitude of the impact of CSG developments in an Australian landscape. The results are highly relevant throughout central and southern Queensland where CSG development is most dense. It also has relevance in New South Wales, where the industry is not as advanced but reserves of CSG are available for exploitation. The study has reviewed changes in the 15 years to 2013, but gives an insight into the potential impacts of the industry as it accelerates toward greater development to meet domestic and export demand.

This work contributes to the political debate surrounding the allocation of natural resources in Australia. Stakeholders such as developers, governments, local residents and activists must use new research to assess the impact of continuing development on the environment, and make changes to operations if necessary. Research in this field is relevant in informing the development and implementation of environmental and planning legislation, as well as company policy and community attitudes. It is through an understanding of the challenges faced during the initial expansion of the CSG industry that stakeholders are able to make better-informed decisions in the future.

6.3 Recommendations for Future Research

This work leads logically to a number of other studies that would increase our understanding of the impacts of CSG activity on land cover change and fragmentation. In particular, the community, the government and industry would benefit from an understanding of the causes of change, and the impacts of change. Future studies might extend this work in a number of ways. This section identifies some of the ways in which future work might address the weaknesses or scope limitations of this study.

While it is well known that land use and land cover do not necessarily correlate, in this study large areas of clearing and regrowth were often closely correlated with cadastral boundaries. Analysis of this link could lead to an understanding of the specific cause of land cover change in the study area. A field examination of cadastral lots identified as being strongly associated with clearing or regrowth may form part of this research. This is a particularly important task in lots near gas wells where change has been observed, but cannot be definitely linked to CSG activity. In light of the literature demonstrating historical and ongoing large scale loss of vegetation in central and southern Queensland, understanding causes of change is essential to target management (Seabrook, McAlpine & Fensham 2006, 2007).

In the literature, edge effects are taken to impact forest 50m-100m from the edge, but this is highly variable. Field examinations of the true size of buffer zones created by CSG development in an Australian environment would help to determine the validity of a choice of 90m in this study. The specific aspects of the environment in the study area, and the nature of the development, could have significant impacts on the true edge effects. These factors include traffic density, the nature of noise pollution from CSG activities, impact of pipelines on Australian fauna, nature of weeds and feral animals affecting the study area and the susceptibility of the specific vegetation types to edge effects. Water pollution and air pollution from CSG activities may also contribute to unique edge effects in the study area. The findings of Collard, Le Brocque and Zammit (2011) indicate that Brigalow Belt vegetation may not be as susceptible to edge effects as other types of vegetation, but this hasn't been demonstrated for other vegetation types in the study area, or for edges other than those adjoining farmland.

The impact of fragmentation is highly species specific. This study has shown that changes in landscape structure have occurred. While these changes may impact on flora and fauna, studies focusing on the lifecycle, habits and nature of particular species or types of species would bring attention to the impact of that change. A study of patches of individual vegetation types could be considered, although the methods used in this paper may not be appropriate if the number of patches is too small.

In the literature, some methods have been developed to filter the impacts of other land use activities on land cover change and fragmentation. In particular, studies that used methods of predicting a landscape after development or retrodicting a landscape before development were able to isolate the effects of oil and gas development from the impacts of other activities occurring in the area at the same time (Finn & Knick 2011; Johnson 2010; Racicot et al. 2014). An approach similar to that taken by Finn and Knick (2011), who modelled a 19th century landscape before the development of oil and gas, could be taken in the study area to superimpose CSG developments on a 1999 landscape. In that way, the changes due solely to CSG developments could be estimated in the study area. In effect this would exaggerate the differences that were observed in this study between the unaltered classified images and the images in which linear infrastructure was well defined in the images as a continuous strip of clear cells.

Little work in the literature considers the impact of fragmentation of agricultural land (as demonstrated in Chapter 2). Only Drohan et al. (2012) and Griffith and Severson-Baker (2003) mention the subject in passing. The application of methods from this study to the inverse of the classified images (patches of cleared land rather than patches of vegetation) could reveal challenges that landholders face in a landscape under CSG development. It must be understood that, while the understanding of the impact of fragmentation on the ecological value of remnant habitats is mature, there is little theoretical work on the impact of CSG or fragmentation on farming practices.

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Appendix A – Project Specifications

The University of Southern Queensland
Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project
Project Specifications

For: Andrew Grigg

Topic: Mapping Changes in the Landscape-Scale Patterns of Vegetation in Coal-Seam Gas (CSG) Development Areas

Supervisor: A/Prof Armando Apan

Enrolment: ENG4111, Semester 1, 2014
ENG4112, Semester 2, 2014

Project Aim: This project seeks to analyse land cover and landscape structure changes in Coal-Seam Gas development areas in the Western Downs region of Queensland.

Revision no: Issue A, 19 March 2014

Programme:

1. Review previous studies on land cover change and vegetation fragmentation, particularly as a result of coal seam gas activity;
2. Map and tabulate changes in land cover between 1999 and 2013 in the study area using classified Landsat images;
3. Determine fragmentation metrics from classified Landsat images taken in 1999 and 2013;
4. Analyse changes in land cover and fragmentation under CSG-induced landscape modification; and
5. Provide a dissertation on the findings of the research.

Further, as appropriate:

6. Analyse the impacts of landscape change on other parts of the environment such as individual ecological communities and other land users.

AGREED:

Name: Andrew Grigg A/Prof Armando Apan

Date: _________________ _________________