Mapping, Modelling and Remote Sensing Buffel grass *(Cenchrus ciliaris)* Infestations in Arid Australia

Thesis submitted for the degree of

Doctor of Philosophy

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DECLARATION

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ABSTRACT

Invasive plants pose a serious threat to ecological, environmental and cultural values of infested regions and can be costly to control. Grass invasions are particularly concerning because they can alter wildfire regimes and change ecosystem function and structure at a global scale. Mapping, monitoring, and understanding invasive species ecology sufficiently to identify habitats prone to invasion are important for containment of the invasive plant. To this effect, remote sensing and spatial information science can be useful.

In arid and semi-arid rangelands worldwide African perennial Buffel grass *(Cenchrus ciliaris L.)* has been introduced to improve pasture. However, it has become contentious because it can rapidly invade and transform non-target landscapes. Most research into Buffel grass relates to its agricultural uses, and little is known about the invasive ecology of the species. There is a need to consolidate existing knowledge, as well as map the current distribution, model potential distribution and improve efficiency in the detection of new infestations in remote landscapes. This research addresses these needs by developing and applying techniques from the spatial sciences to map and model Buffel grass distribution in remote, arid Australia.

For controversial invasive species like Buffel grass, awareness about the ecological dangers of allowing spread to continue unchecked is important. Here, a new, comprehensive review is presented of the ecology, distribution and biodiversity impacts of Buffel grass when behaving as an invasive species. Importantly, this review also lays foundations for research into localised habitat requirements, setting the scene for all subsequent components of this research. The review reveals that temperature is a primary limitation to distribution at a global scale, soil texture may be a significant habitat parameter at localised scales and disturbance is required for seedling emergence. It is strongly suspected that Buffel grass fuelled fires are responsible for declining numbers of characteristic arid plants, the Saguaro Cactus (Arizona, USA) and the River Red Gum (Australia), and worldwide, arid landscapes stand out as requiring urgent control.

The distribution of Buffel grass in invaded landscapes in arid southern Australia is not explicitly known. Over 3100 km of South Australian roads were surveyed to document current Buffel grass distribution in collaborative work with government. The grass was found to be wide ranging along major highways, but was mostly only sparsely distributed.

Empirical modelling of species' distribution helps identify local environments that may be prone to invasion, and is becoming an increasingly important step in effective management planning. Buffel grass roadside survey data were used in an exploratory regression analysis to identify environmental parameters of the species' distribution across regional South Australia. Roadside populations were recorded separately from populations away from the road on adjacent land and considered as separate dependant variables for predictive modelling. The models return strong results and on the basis of these we make management recommendations that containment of propagules along roadsides will be the most important factor in preventing spread and that where roads intersect drainage lines should be focal points for monitoring.

Remote sensing presents as an ideal mode for mapping and monitoring invasion as it affords a landscape scale view and can be cost effective compared with laborious field work. However, it is challenging to implement because of the overall similarity of the spectra of different grasses and variability of Buffel grass stands, and photosynthetic status within stands over space and time. In this thesis, Buffel grass discrimination is trialled using high spatial resolution satellite imagery and aerial photography. Multispectral (eight-band) satellite imagery (2 m GSD) namely, Worldview-2 was found to effectively map dense infestations, but for early detection of emerging infestations, it is shown that aerial imagery spatial resolution no coarser than 5-6 cm GSD is required.

Presented in this thesis are tools needed to assess, monitor, predict and ultimately mitigate Buffel grass spread in arid Australia, including maps of present distribution, techniques for mapping and monitoring invasion over time, and an understanding of the species ecology as an invader to predict regions vulnerable to infestation. The methodology for roadside survey which makes the data more applicable to landscape-wide predictive habitat modelling could be adopted for any species where roads are considered a vector for spread. The research has important implications for Buffel grass management in regional arid Australia, and also for understanding the exotic distribution of Buffel grass worldwide. For detection of emerging Buffel grass infestations at a regional scale, aerial survey is recommended. Use of satellite imagery for monitoring of larger infestations is one area for future research.

PUBLICATIONS ARISING FROM THIS THESIS

Refereed

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Marshall, V.M, Lewis, M., Ostendorf, B. (2013) "Detecting new Buffel grass infestations in Australian arid lands: evaluation of methods using high-resolution multispectral imagery and aerial photography" Environmental Monitoring and Assessment (Accepted: 30 September 2013, *In press*)

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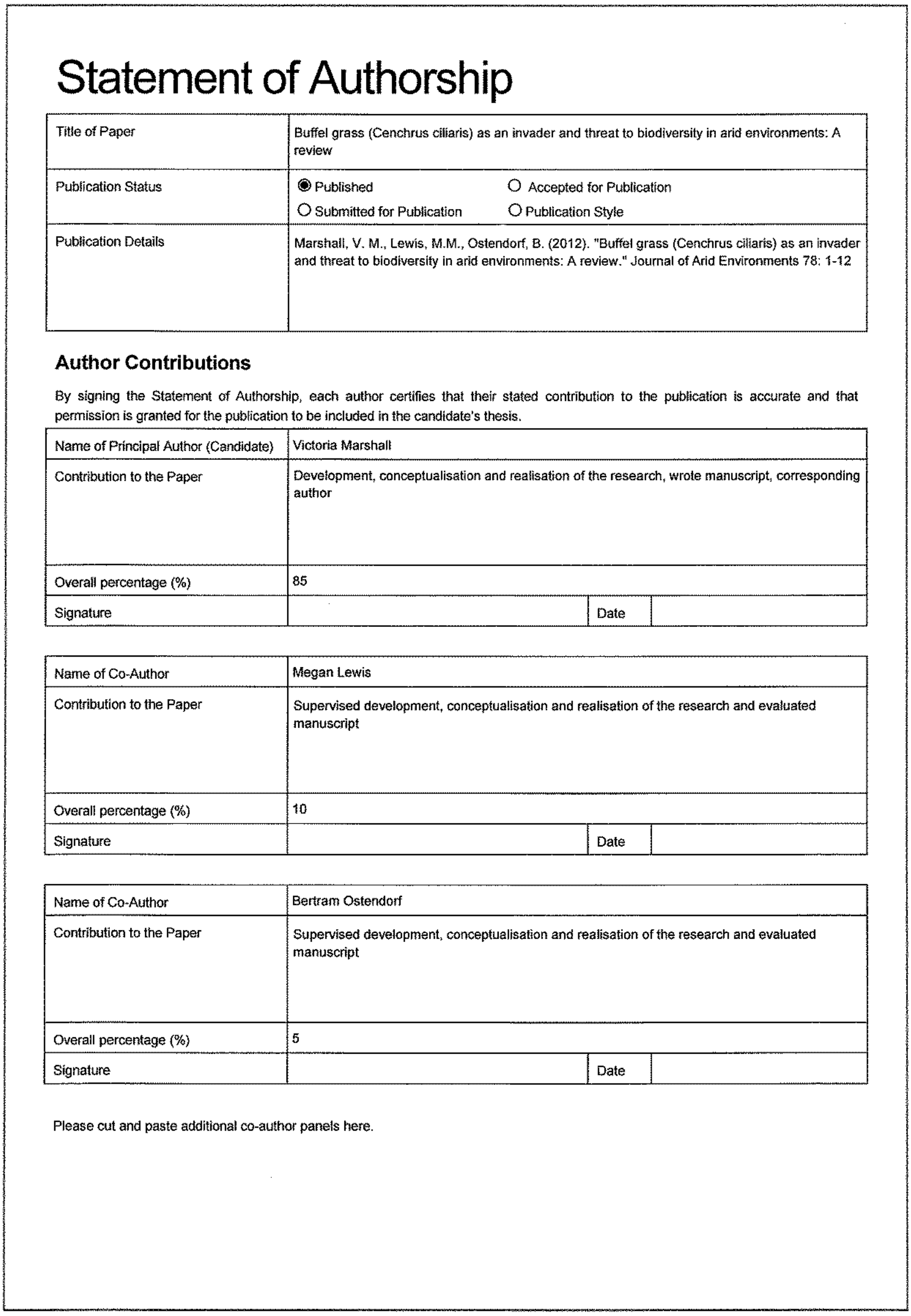
Marshall, V. M., Lewis, M. & Ostendorf, B. (2012) "Do additional bands (Coastal, NIR-2, Red-edge, and Yellow) in Worldview-2 multispectral imagery improve discrimination of an invasive tussock, Buffel grass *(Cenchrus ciliaris)*?" In: XXII International Society of Photogrammetry and Remote Sensing Conference, August 25–September 1 Melbourne, Australia

STATEMENTS OF AUTHORSHIP

CHAPTER 2



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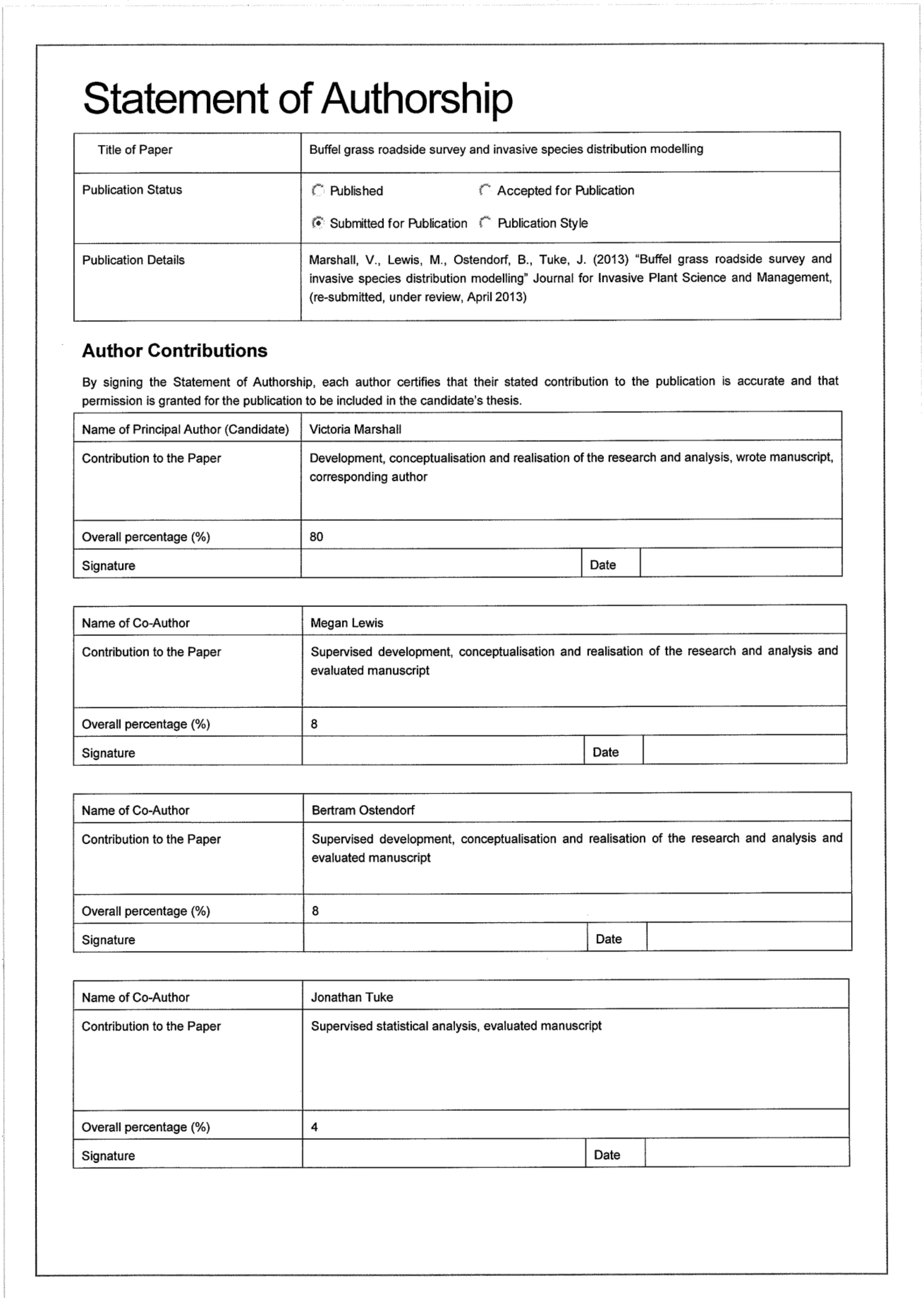

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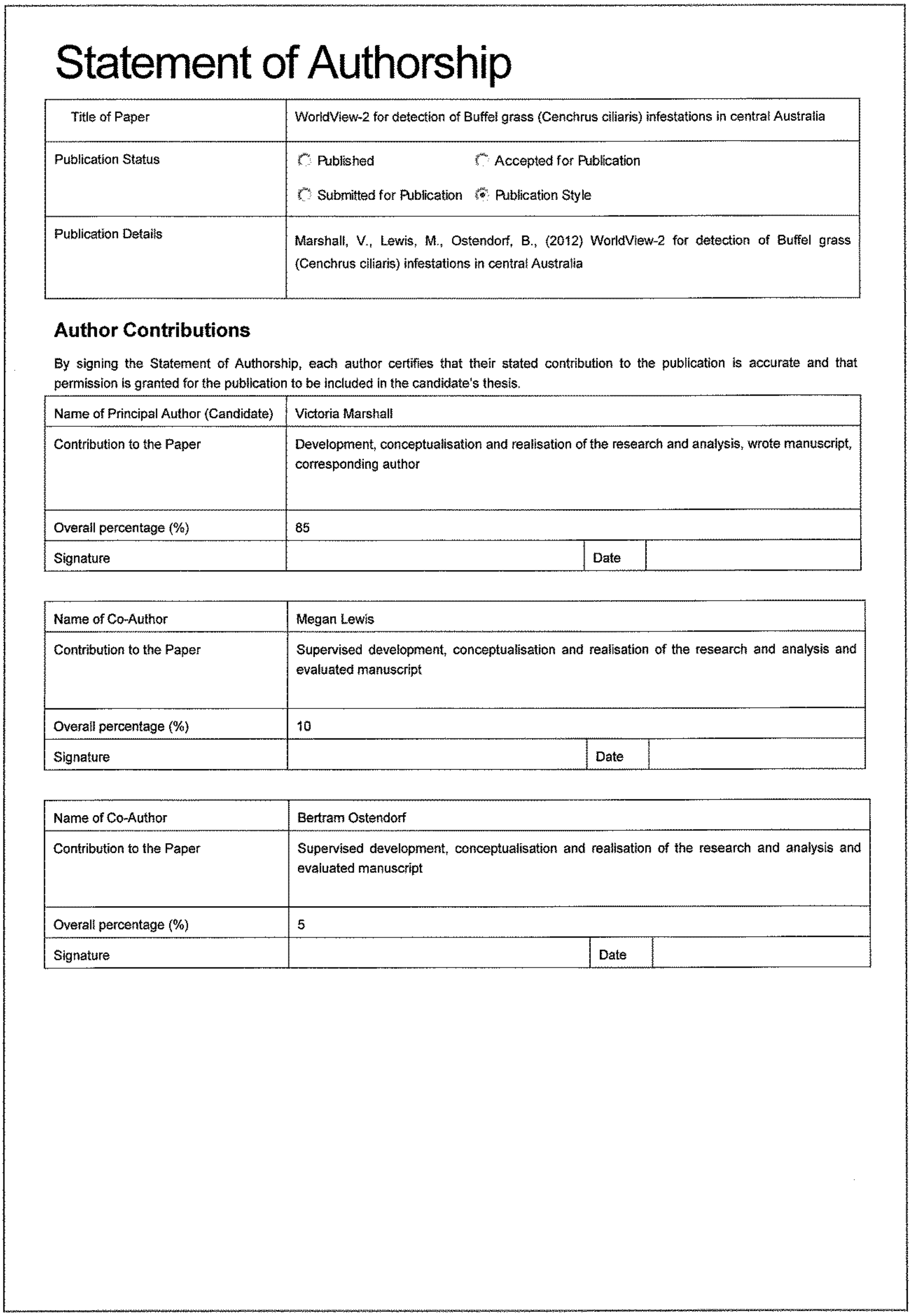

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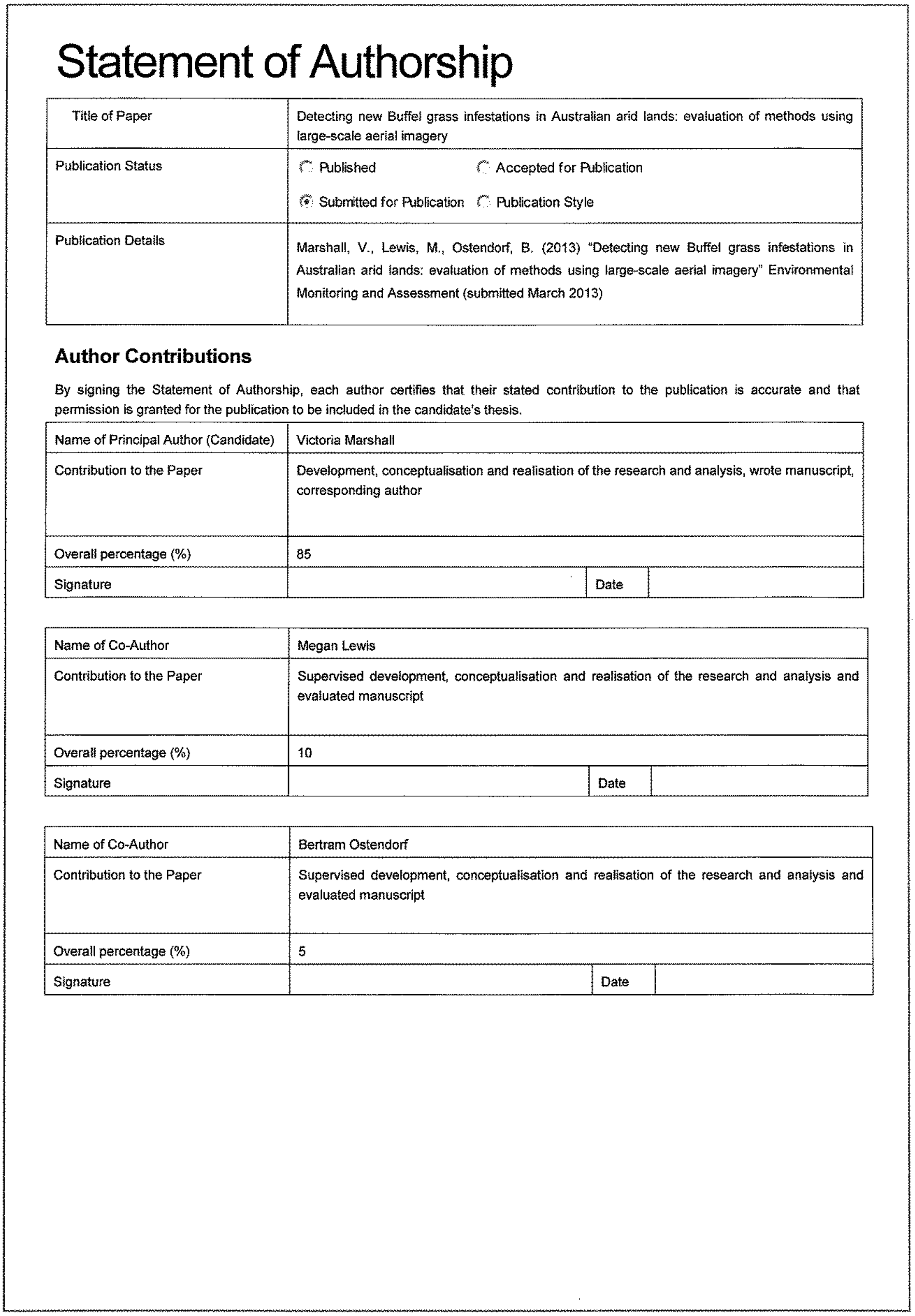
CHAPTER 5



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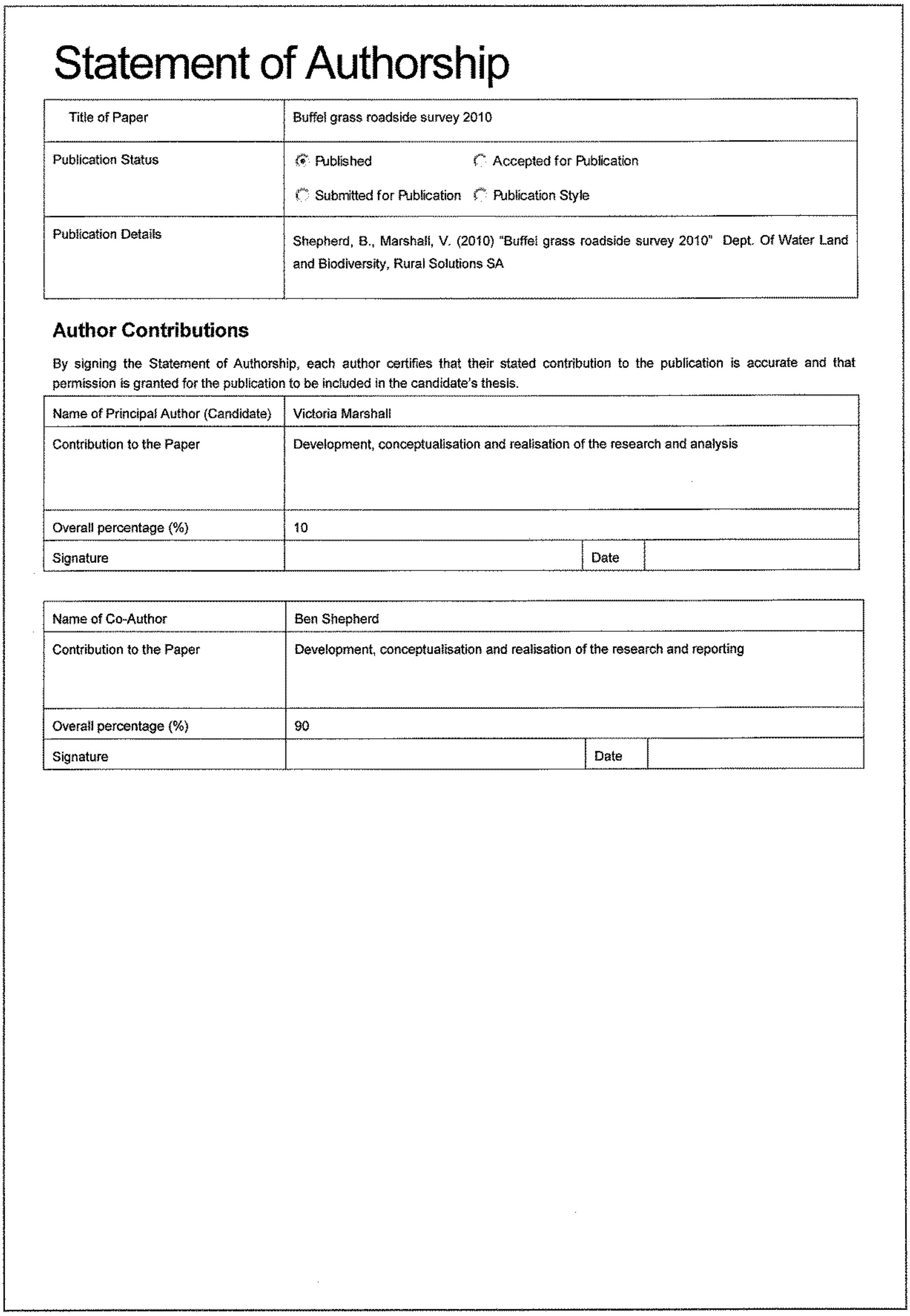
APPENDIX ONE



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For Mum

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Chapter One

Introduction

1.0 INTRODUCTION

"An invasive species is a species occurring, as a result of human activities, beyond its accepted normal distribution and which threatens valued environmental, agricultural or other social resources by the damage it causes." (Australian Department of Sustainability Environment Water Population and Communities 2011)

Invasive species are recognised as a primary cause of global biodiversity loss, homogenising the world's flora and fauna (Dirzo et al. 2003). The cost of control is phenomenal (Olson et al. 2002). Typically mitigation, containment or eradication is desired; however, control and eradication become controversial if the species has economic benefits.

A topical example and the focus of this research is Buffel grass *(Cenchrus ciliaris L. Pennisetum ciliare)*, an invasive species of economic significance throughout arid regions of Australia, Mexico and the United States (Arriaga et al. 2004; Jackson 2005; Franklin et al. 2006; Eyre et al. 2009; Schlesinger et al. 2013).

Its value lies in its unique suitability for use as pasture and erosion control throughout arid and semi-arid environments that ordinarily support low levels of grass in the understory (Walker et al. 1990; Harwood et al. 1999; Praveen et al. 2005; Bhattarai et al. 2008; Guevara et al. 2009; Tefera et al. 2010). Buffel grass is apt for these purposes because it has high nutritional value for sheep and cattle, high tolerance to drought, an ability to withstand heavy grazing, a deep stabilising root system and it responds quickly to rainfall events (Phillips 1931; Lazarides et al. 1997). It is also one of few pastoral species that is apomictic, meaning it can produce clones from seed, a trait which offers huge potential for the development and distribution of cultivars and agro-types specifically suited to pastoral grazing (Akiyama et al. 2005; Ozias-Akins et al. 2007; Conner et al. 2013). However, the characteristics which make Buffel grass so versatile and suited to a range of harsh conditions also make it an aggressive invader of non-target environments.

Buffel grass seed spreads easily by wind, along water courses and via human or animal traffic. Plants emerge quickly in disturbed environments, requiring a loose soil surface and moisture for germination (Cameron 2004; Ward et al. 2006). Once established, it can quickly invade adjacent ecosystems, negatively impacting species richness (Collins et al. 1991; Bestelmeyer et al. 1999; Fairfax et al. 2000; Blanco et al. 2005; Clarke et al. 2005; Jackson 2005; Flanders et al. 2006; Franklin et al. 2006; Hannah et al. 2007), and displacing native flora and fauna such as the iconic River Red Gums *(Eucalyptus camaldulensis)* of Australia (Centre for Arid Zone Research 2001) and the Saguaro cacti *(Carnegiea gigantea)* of the Sonora Desert of Mexico and the USA (Schiemeir 2005).

The most environmentally and culturally devastating aspect of Buffel grass invasion is its impact on wildfire. Buffel grass produces high volumes of dead standing matter which ignite easily and burn hotter and faster than many regionally native grasses (D'Antonio et al. 1992; Martin-R et al. 1999; Schiermeier 2005; Smyth et al. 2009; Schlesinger et al. 2013). Following wildfires, it is often first to remerge on ash beds and the cumulative result is a rapidly formed monoculture of Buffel grass that is undesirable outside of pastoral country (Miller et al. 2010). The overall result of so many local changes in ecosystem function may be sufficient to affect climate, water quality and atmospheric composition (D'Antonio et al. 1992).

The importance of controlling Buffel grass from an ecological and biological conservation perspective is clear. Yet, for two reasons, many local governments and communities are reluctant to control its spread. Firstly, most reports into the impacts of Buffel grass invasions on biodiversity and conservation are presented in grey literature only and there is little objective and quantitative evidence of its effects in the published literature (Web of Science, 2011). This has made it difficult to construct a compelling argument for the control of this highly valued pastoral species. Secondly, Buffel grass has naturalised across so many landscapes that many stakeholders feel control is out of reach. Thus, there is need for new research into the nature of Buffel grass as an invader and to synthesise current literature as a stronger basis for effective species management.

A crucial first step for effective management of plant invasions, particularly for species where total eradication is not necessarily possible or desired, is to prioritise areas for conservation, control and surveillance. Prioritising “at risk” areas requires knowledge of the current and potential distribution of the species as well as understanding of how and why it spreads (Underwood et al. 2004; Williams et al. 2008). For Buffel grass, this information is lacking, particularly in the Australian context.

Approaches to mapping the distribution of species are scale, time and cost dependant; for rapid assessment at regional scales, roadside survey is a common approach (Rahlao et al. 2010). It is particularly effective for mapping exotic plants because roadsides are susceptible to invasion and are accessible for sampling (Milton et al. 1998; Reese et al. 2005). The vulnerability of roadsides to invasion relates firstly to the influx of propagules; road traffic can be a vector for seed dispersal (Christen et al. 2006; Zwaenepoel et al. 2006; Taylor et al. 2012; Von der Lippe et al. 2012). Secondly, it relates to the roadside conditions that support seedling establishment; disturbed, loosened soils (Hobbs et al. 1992; Donovan et al. 2010), and a uniquely suited microclimate that is influenced by radiant heat from the road, water runoff and altered nutrient cycling (Haan et al. 2012). It is widely accepted that roadsides act as corridors for the spread of Buffel grass into natural ecosystems (Brooks et al. 2005; Kalwij et al. 2008), which further endorses roadside survey as an appropriate means of assessment and roads as high priority areas for management of this plant.

Anticipating the potential distribution of a species is complex because ecological processes operate at different scales (Nielsen et al. 2008; Trivedi et al. 2008), and because there is a dynamic relationship between species, environment, competition, predation and disease over space and time. There are numerous approaches to constructing predictive distribution models but overall they pertain to either the realised niche (empirical models) or the fundamental niche (mechanistic models) (as per Hutchinson's Niche Theory (Hutchinson 1957) and Levin's strategy of model building in population ecology (Levins 1966)). Distinction between the two is important because they have different uses. Mechanistic models are useful at large spatial scales, and to predict species responses to environmental or climate change, while empirical models are superior for localised, highly accurate predictions (Guisan et al. 2000). To target control efforts, regionally accurate empirical models are required, and this is where our focus lies.

Data availability is the major limitation to empirical modelling. Ideally, predictive habitat models are based on systematically designed sampling that fully and accurately represents the species' presence and absence across a landscape (Hirzel et al. 2002). However, data are rarely collected specifically for modelling purposes, and as discussed, baseline datasets of regional distribution are commonly obtained via roadside survey.

Where the goal is not to model potential roadside distribution, but to extrapolate across the landscape, roadside survey data has limited usefulness. This is because, roadside data are geographically biased by the position of roads in the landscape (being strongly influenced by terrain, for example), and because roads act as corridors for invasive species spread (Reese et al. 2005). Additional bias results from the road-effect zone. This is defined as the area over which significant ecological effects span outward from the vehicular route. It is asymmetric, with complex boundaries, and unequal effect distances that reflect micro-variations in the ecosystem that the road bisects (Forman et al. 1998). The effect of roadside bias on landscape-wide predictive habitat modelling has been little studied (Kadmon et al. 2004; Austin 2007).

Furthermore, there is an inherent problem with empirically modelling the potential habitat of a species which is actively invading a new environment. It violates a fundamental assumption of predictive habitat modelling that the species-environment relationship should be in equilibrium (Austin 2002; Elith et al. 2009). Models that do not meet these assumptions often incorrectly define the potential range of the species because they wrongly interpret “absence” as “uninhabitable” (false negatives) or “presence” as “naturalisation of the species in the environment” (false positives) (Mack 1996; Curnutt 2000; Thuiller et al. 2005). However, for regional modelling of exotic plant species within an invaded system, model predictions have been improved by limiting assessment to established or naturalised populations and by incorporating proxies of propagule pressure into the model (Dullinger et al. 2009; Fensham et al. 2013). Propagule pressure may be the single greatest determinant of invasion success and when incorporated as a predictor variable, the model becomes not only an indicator of habitat suitability but of its susceptibility to invasion as well (Eschtruth et al. 2009).

Ideally, habitats susceptible to invasion should be regularly monitored for early detection of new infestations and to mitigate spread of established populations. Field-based mapping and monitoring is only feasible over localised areas, typically restricted by road access to sites of particular significance, or to sites identified as appropriate for strategic control where an isolated occurrence is observed. Moreover, field-based methods are not easily repeated and they are inadequate in the remote desert landscapes of Australia, where Buffel grass thrives and is widespread away from roads. The alternative is to take a remote sensing approach.

Remote sensing has been used for decades to map the biophysical characteristics of vegetation over space and time (Lawrence et al. 2006) including for the delineation of vegetation communities (Chastain et al. 2008) as well as species (Homer et al. 2012), monitoring functional responses over time (Lawley et al. 2011) and measuring above ground biomass (Yan et al. 2013). Delineation is dependent on the spatial, temporal, and biophysical characteristics of the target, as well as the sensors' resolutions: spatial, spectral, temporal and radiometric (Xie et al. 2008). Achieving all forms of high resolution usually results in a restricted spatial extent and high acquisition cost.

In general, species-level mapping has been most successful when the target species possessed distinctive spectra, had a large structure or grew in large stands relative to the ground resolution of imagery, showed vigorous population growth; and when the phenological stages of growth were taken into account during spectral signature collection (Ustin et al. 2002; Ge et al. 2006; Andrew et al. 2008; Hestir et al. 2008; Wang et al. 2008; Blumenthal et al. 2009; Jia et al. 2011; Padalia et al. 2013). This presents challenges for the remote detection of Buffel grass because most grasses are spectrally similar, the size of stands is variable and with unknown limits, vigorous growth is a response to rainfall and is not strictly seasonal, and there is a degree of intra-species variation.

Hyperspectral sensors have proven to deliver a high degree of accuracy for species-level discrimination of other non-woody perennials such as *Centaurea maculosa* (Spotted knapweed) (Lass et al. 2002), *Glycine max* (Soybean) (Gray et al. 2009) *Heracleum mantegazzianum* (Giant hogweed) (Müllerová et al. 2013). When phenological characteristics were taken into account, Ishii et al. (2013) demonstrated that aerial hyperspectral imagery (1.5 m ground sample distance (GSD)) could be used to delineate the alien species *Solidago altissima* (Tall goldenrod) at its early invasion stage in the understorey of a moist tall grassland. However, the advantages of hyperspectral sensors do not always justify the high cost and large volumes of redundant data requiring expert interpretation; as a result it is impractical for most weed management authorities to utilise this imagery.

The recently launched (January 2010) Digital Globe sensor, Worldview-2, offers a middle ground between high spatial and high spectral resolutions (2 m GSD, pan-sharpened 0.5 m GSD; 8 spectral bands, visible- NIR) that has been lacking. Its application to vegetation mapping has since been demonstrated (Cui et al. 2013; Doody et al. 2013; Garrity et al. 2013) but not for Buffel grass.

There have been several published attempts to remotely detect Buffel grass in the Sonoran Desert of the USA and Mexico (Franklin et al. 2006; Brenner 2011; Olsson et al.

2011; Olsson et al. 2012) and Australia (Puckey et al. 2007). Moderate resolution satellite data (MODIS and Landsat) were useful for monitoring large converted pastures over several years (Franklin et al. 2006; Brenner 2011), but less useful for distinguishing invasive patches in heterogeneous mixed desert scrub (Olsson et al. 2011). For this purpose, high density patches were best discriminated by integrating field collected hyperspectral measurements of plant spectra (Olsson et al. 2011). The classification was dependant on the phenological response of Buffel grass to the monsoon season; the monsoonal desert ecosystem is unique to the Sonoran Desert and this phenologically dependant detection method may not be applicable elsewhere.

To detect new emerging infestations in natural landscapes, individual plants must be distinguishable and for this high spatial resolution data are required. This has only been trialled via aerial survey, whereby observations were made from the aircraft to document infestations (Puckey et al. 2007). As well as providing the high spatial resolution required to detect small infestations, aerial sensors have an advantage over satellite sensors in that timing is extremely flexible. This is critical when working with grasses that have fleeting growth-stages. The challenges associated with aerial survey and the interpretation of aerial photographs relate to the limited spatial coverage of scenes, the quality of images being strongly weather dependant, data management, processing time, cost and most importantly, uncertainty regarding the accuracy of classification and end-maps (Gergel et al. 2010). It is for these reasons that aerial assessments are often underutilised by natural resource managers in favour of field-based approaches. Research into optimal survey strategies and image classification techniques is urgently required for application to Buffel grass management in Australia.

1.0.1 Research objectives

The overall goal of this research was improve our understanding of Buffel grass as an invasive species and to develop the tools needed to assess, monitor, predict and ultimately mitigate Buffel grass spread in arid Australia. This included creation of new maps of present distribution, techniques for mapping and monitoring invasion over time and for predicting regions vulnerable to infestation. The specific objectives were to:

1. comprehensively review literature relating to Buffel grass ecology as an invasive species to inform this PhD research (Objectives 2 – 5) as well as providing a foundation resource for scientist and natural resource managers invested in Buffel grass invasion ecology and management,

2. collate currently available distribution data, and conduct a new a survey to provide baseline information about Buffel grass distribution in regional South Australia,

3. develop and explore a new roadside survey sampling technique suitable for species distribution modelling,

4. construct empirical models based on roadside survey data to predict roadside habitats as well as habitats on land adjacent to the road suitable for Buffel grass growth in arid South Australia, and

5. explore the potential of remote sensing for detection of Buffel grass populations in Australian arid lands.

1.0.2 Study context

In Australia, where this study is based, Buffel grass has been a backbone of the sub-tropical, semi-arid pastoral industry since the 1920s, and an important soil stabiliser around central Australian airports, towns and train lines since the 1970s (Friedel et al. 2007b). In certain environments, it has rapidly spread into indigenous ecosystems, threatening native flora and fauna. Today, it forms blankets over parts of the central Australian landscape; climatic modelling indicates that greater than 90% of Australia could support its growth, with only temperate climates in the far south-east safe from invasion (Lawson et al. 2004). In South Australia, few pastoralists are reliant on Buffel grass, yet it is becoming widespread. Anecdotal evidence suggests that it enters the state along major highways and spreads out from road verges where environmental conditions are appropriate. The extent of invasion is unknown.

The primary motivator for this research is that Buffel grass threatens the environmental and cultural integrity of arid and semi-arid South Australia, but particularly of the aboriginal-trusted Anangu Pitjantjatjara Yankunytjatjara (APY) lands. The APY are one of three key aboriginal landholding authorities within the Alinytjara Wilurara Natural Resource Management (AW NRM) region. The AW NRM region occupies 107, 000 square kilometres (26% of South Australia). In this region, conserving the natural landscape is particularly significant to support aborigines living off the land; hence the impacts of weed invasion and fire alteration are priority issues.

In October of 1987 Buffel grass was direct seeded around the aboriginal community of Kalka, in the far north-west corner of the APY lands, along with *Cenchrus setigerus* and native drought tolerant shrubs, *Atriplex nummularia*, *Acacia kempeana* and *Acacia ligulata*, to combat dust storms on the alluvial flats. Dust became a problem in this region after an uncontrolled wildfire burnt a substantial area near the settlements: drought followed, and vegetation never regenerated. As a result of the direct seeding in 1987, this region is now largely dominated by Buffel grass. The inhabitants of this area, the Pipalyatjara people, already notice having to travel further for hunting and gathering of traditional foods. In an interview, one of the traditional owners listed Bush Tomatoes, Kangaroos, and Daisies among the native flora and fauna locally disappearing. The communities do not like Buffel grass-fuelled fires and refer to Buffel grass in translation as “evil grass”.

Unlike other Australian States with extensive arid rangelands, South Australia has an opportunity to prevent Buffel grass from becoming permanently established across a significant portion of this biome (Biosecurity SA 2012). To do this, current regional distribution maps, identification of habitats prone to invasion, and methods for improved efficiency in the detection of this rapidly spreading grass are required to mitigate spread. Additionally there is a need to raise community awareness about Buffel grass invasion to minimise human-facilitated spread and establishment.

1.0.3 Thesis structure

This thesis is presented as a series of research papers and reports published or intended for publication. Each chapter addresses one or more of the defined research objectives. This section outlines the chapter themes and describes how they fit together. Note that papers are collaborative; the breakdown of contributions is testified in the "Statement of Authorship" (pages vii –xv) and any reference to work *we* completed is to be considered in this context.

Chapter Two: Marshall, V., Lewis, M., Ostendorf, B. (2012) "Buffel grass *(Cenchrus ciliaris)* as an invader and threat to biodiversity in arid environments: A review" Journal of Arid Environments, 78, 1-12

This chapter addresses Objective One. Buffel grass is an invaluable pastoral species in arid rangelands around the globe that can also be an aggressive invader of non-target environments. Little is known about the invasive capacity and adverse biodiversity impacts of Buffel grass. This knowledge is required if we are to successfully detect invasions at early stages and prevent further spread. There is a wealth of information available relating to Buffel grass as a pastoral species. However, tapping into this resource requires reading widely across the agronomic, plant science and ecological literature. In light of this we present a comprehensive review of literature on Buffel grass ecology, distribution and impacts on biodiversity intended as a resource for both researchers and managers. We chose to publish in the Journal of Arid Environments to reach a broad audience, not just plant science researchers or natural resource managers, but anyone interacting with arid environments, which we identify through our research as requiring urgent attention.

Chapter Three: Marshall, V., Lewis, M., Ostendorf, B., Tuke, J. (2013) "Buffel grass roadside survey and invasive species distribution modelling" (Undergoing revision)

This chapter addresses Objectives Two, Three and Four. First, in a collaborative assignment with government, we documented the current regional distribution of Buffel grass along selected roadsides in arid South Australia (Appendix 1). Survey data were then used to construct an empirical model of the potential exotic distribution of Buffel grass. Ordinarily, predictions would only be applicable to the roadside environment because roadside observations are not representative of the wider landscape. In this chapter we hypothesise that if at the time of survey observers recorded roadside observations separately from those observations away from the road on adjacent land, then that data would be more indicative of wider landscapes vulnerable to infestation. This chapter is currently undergoing revision, and is intended for publication in the *Journal of Environmental Monitoring and Assessment*.

Chapter Four: Marshall, V., Lewis, M., Ostendorf, B., (2012) WorldView-2 for detection of Buffel grass *(Cenchrus ciliaris)* infestations in central Australia

This chapter addresses Objective Five. It presents a minor study into the use of high resolution multispectral satellite imagery for mapping Buffel grass. A satellite-based remote sensing approach to mapping is important for ongoing monitoring to be feasible. We use a satellite-acquired WorldView-2 (WV-2) scene captured west of Alice Springs in central Australia where Buffel grass is known to be widespread at high densities as a test subject. The WV-2 sensor with 2 m ground sample distance (GSD) and 8 spectral bands across the visible and near-infrared (NIR) was launched in 2010 not long before we undertook this study. Thus, one of our key research questions was not just whether we can detect Buffel grass, but whether the eight-band sensor offers a tangible improvement over traditional four-band (visible –NIR) multispectral imagery for Buffel grass discrimination. To test this, we examine spectral separability of land cover classes based on 4 and 8 bands, then make recommendations for future use. Aspects of this chapter have been presented as two non-refereed papers, one at the XXII International Symposium of Photogrammetry and Remote Sensing (Melbourne, 2012), and another to the Digital Globe 8-Band Challenge, which was conditional on receipt of imagery. The thesis copy contains updated figures and text.

Chapter Five: Marshall, V., Lewis, M., Ostendorf, B. (2013) "Detecting new Buffel grass infestations in Australian arid lands: evaluation of methods using high-resolution multispectral imagery and aerial photography" Environmental Monitoring and Assessment (Accepted: 30 September 2013, *In press*)

This chapter presents a major study addressing Objective Five. The key issue for Buffel grass managers in Australia is the vast desert environment which is difficult to access and monitor. Remote sensing presents as an ideal tool for mapping and monitoring, but if it cannot be applied to reliably detect infestations in their infancy, field work will always be required. Aerial photography can be acquired at sufficient resolutions to detect individual plants, but because of uncertainty in interpretation, analysis and classification it is often overlooked by natural resource managers. In this paper, we explore the use of high resolution aerial photography (5 cm ground sample distance (GSD)) and four-band (colour-NIR) multispectral imagery (25 cm GSD) for Buffel grass detection in central Australia. We evaluate four traditional aerial photography classification methods for their application to Buffel grass mapping and make recommendations for future use. The paper has been accepted for publication by the *Journal of Environmental Monitoring and Assessment* (30 September 2013) and offers remote sensing as an alternative to traditional field methods for monitoring and evaluation of invasion. The research is directly applicable to APY land management as the study is based in Kalka.

Chapter Six: Conclusions

In this chapter the findings of the research are summarised and the major contributions that this PhD makes to invasive plant science are outlined. Applications of the findings to prediction, survey, monitoring and management of Buffel grass are discussed, and future research needs are identified.

Appendix 1: Shepherd, B., Marshall, V. (2010) "Buffel grass roadside survey 2010" Dept. Of Water Land and Biodiversity, Rural Solutions SA

This appendix relates to Objective Two. It is a South Australian Government report which documents the methodology, results and management recommendations of a Buffel grass roadside survey conducted in May 2010 through regional South Australia. The survey was conducted for and in collaboration with Biosecurity SA and Rural Solutions SA. My contribution to the development and conceptualisation of this survey is substantial and it is a significant component of this PhD research. The survey route was designed to intersect environmental gradients as well as fill gaps in the known distribution. Data on the known distribution was based on opportunistic records, which I compiled from numerous online and private records. The methodology of the survey is uniquely designed so that the data might be useful in habitat modelling. The methodology requires that populations away from the road verge are recorded separately from roadside populations. This innovation was devised and trialled as a part of this PhD research and is thoroughly explored in Chapter Three. The survey was conducted by Rural Solutions SA, who also formulated the management recommendations.

Chapter Two

Buffel grass *(Cenchrus ciliaris)* as an invader and threat to biodiversity in arid environments: A review

Citation: Marshall, V., Lewis, M., Ostendorf, B. (2012) “Buffel grass *(Cenchrus ciliaris)* as an invader and threat to biodiversity in arid environments: A review” Journal of Arid Environments, 78, 1-12

Key words: rangeland pastoral species, biological invasion, habitat requirements, Pennisetum ciliare

Abstract. Popular pastoral species, Buffel grass *(Cenchrus ciliaris)* is receiving long overdue attention as an invasive weed that poses serious threats to biodiversity conservation worldwide. Most research focuses on the species as forage plant and is largely published in agricultural and grey literature. Meanwhile, there is a dearth of information about the species' ecology in natural landscapes despite strong evidence from field workers and managers that the species is an aggressive invader and threat to biodiversity in many environments. We present a comprehensive review of the ecology, distribution and biodiversity impacts of Buffel grass when behaving as an invasive species. Foundations are laid for research into localised habitat requirements of the species that will aid in the management of Buffel grass invasions now and into the future.

2.0 INTRODUCTION

The global cost of controlling biological invasions is phenomenal. Typically, mitigation, containment or eradication of the invasive species is desired; however, control and eradication become controversial if the species is economically significant.

Buffel grass (*Cenchrus ciliaris L.*) is grown widely in tropical and sub-tropical arid rangelands around the globe because of its high tolerance to drought and capacity to withstand heavy grazing. Outside its natural range, Buffel grass can rapidly invade native vegetation, roadsides and urban landscapes, altering the wildfire regime and displacing the native flora and fauna. Due to the economic benefits of the species, eradication is controversial and weed management authorities are ill-informed to effectively target management actions. While over 400 research papers have been published relating to the improvement of Buffel pasture, less than 20 relate to its impact on biodiversity and even fewer describe its nature as an invader (Web of Science, June 2011). Strategic control of Buffel grass invasions requires knowledge of regions infested with or vulnerable to invasion, as well as a willingness from the community to be involved in controlling its spread, all of which are currently lacking.

Presented here is a review of the ecology, distribution and biodiversity impacts of Buffel grass in invaded environments, as well as a synthesis of physiological characteristics relevant to an understanding its behaviour as an invader. The paper aims to increase awareness about the ecological dangers of Buffel grass invasions continuing unchecked and to improve understanding about the ecology of Buffel grass for the purpose of managing invasions.

2.0.1 The Controversy

The eradication of Buffel grass is controversial because the species is highly valued as a pastoral species and more recently for mine site rehabilitation and erosion control (Walker et al. 1990; Harwood et al. 1999; Praveen et al. 2005; Bhattarai et al. 2008; Guevara et al. 2009; Tefera et al. 2010). Buffel grass is uniquely suited to these purposes because it has high nutritional value for sheep and cattle, high tolerance to drought, an ability to withstand heavy grazing, a deep stabilising root system and responds quickly to rainfall events (Phillips 1931; Lazarides et al. 1997). Buffel grass is also one of few pastoral species that is apomictic, meaning it can produce clones from seed, a trait which offers huge potential for the development and distribution of cultivars and agro-types specifically suited to pastoral grazing (Akiyama et al. 2005; Ozias-Akins et al. 2007). However, the characteristics which make Buffel grass so versatile and suited to a range of harsh conditions also make it an expert invader of non-target environments and from an environmental point of view it is important to prevent further spread of this weed. There is a lack of objective and quantitative research into the adverse impacts of Buffel grass invasions on biodiversity. Although this is changing, it remains difficult to construct a compelling argument for the control of this highly valued pastoral species.

2.1 ORIGIN AND EXOTIC DISTRIBUTION

Buffel grass occupies extensive areas of the globe within 45 degrees North and South of the Equator. We base this statement on a thorough examination of scientific literature as well as web-based publications and personal communications regarding the presence of the species across states and countries, the results of which are presented in Figure 1. It should be noted that this map is based on sparsely distributed locational records. It is intended to indicate the expanse of states and countries that may be required to actively manage this weed, and is by no means a regionally accurate depiction of the species' extent. The grass is native to tropical and subtropical arid regions of Africa and western Asia; its exotic distribution spans parts of Australia, USA, Mexico and South America (Centre for Arid Zone Research 2001; United States Department of Agriculture 2010). The intercontinental dispersal of Buffel grass has been predominantly human-driven, thus understanding the species' dispersal history may be critical to control further spread (Pauchard et al. 2006).

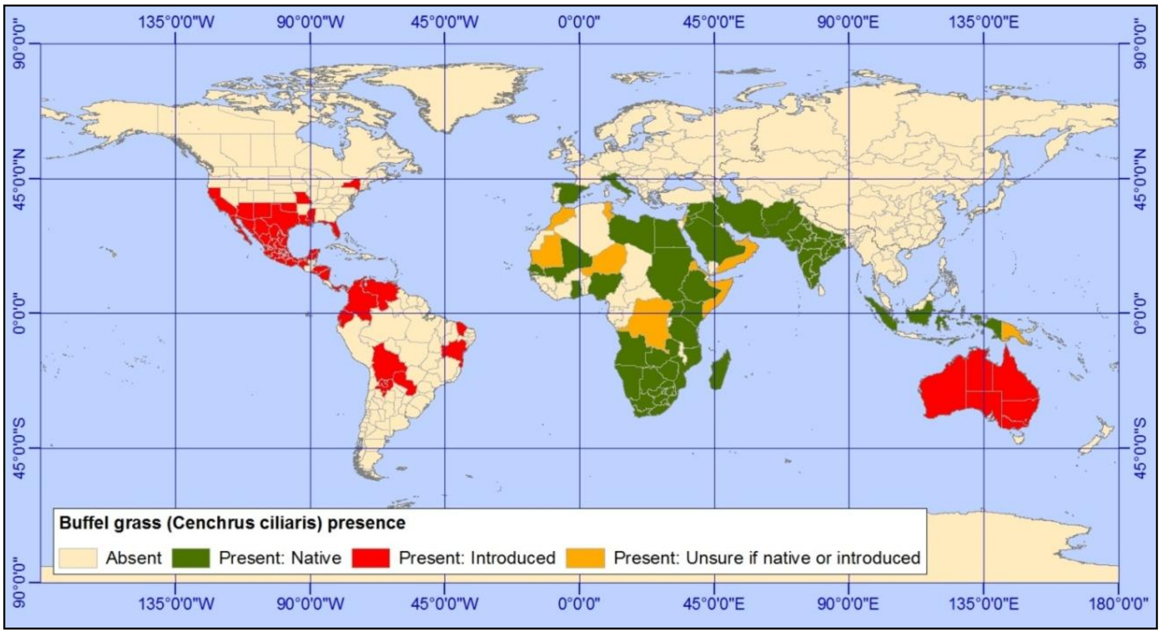

Figure 1 The native and exotic distribution of Buffel grass to state or country level compiled from published and internet sources. Buffel grass is native (green) to Afghanistan, Angola, Botswana, Canary Islands , Egypt, Ethiopia, Ghana, India, Indonesia, Iran, Iraq, Israel, Italy, Jordan, Kenya, Libyan Arab Jamahiriya, Mali, Madagascar, Mozambique, Namibia, Nigeria, Pakistan, Saudi Arabia, Senegal, Spain, Sudan, Swaziland, Syrian Arab Republic, Tanzania, Uganda, Zambia, and Zimbabwe (Arizona-Sonora Desert Museum Staff and Volunteers, 2008). The species is exotic (red) in Australia, the United States (incl. Hawaii (1932), Arizona (1946), California, Florida, Louisiana, Mississippi, Missouri, New Mexico New York and Texas (1940s), Virgin Islands, and Oklahoma), and parts of central and south America including Mexico (Centre for Arid Zone Research, 2001; United States Department of Agriculture, 2010). Buffel grass is present, but may be native or introduced (yellow), in Central African Republic, Mauritania, Niger, Oman, Somalia, Yemen and Zaire. Buffel grass is shown as "Absent" (beige) where there is a lack of data confirming its presence and thus does not truly represent absence of the species.

2.1.1 History of intercontinental dispersal

Buffel grass is one of several African perennial grasses that were widely introduced around the world to better pastoral industries in the early 1900s. Considered to be a "wonder crop" (Hanselka 1988) for its ability to withstand drought and rapidly respond to rains, Buffel grass was introduced into USA, Mexico, and Australia around 100 years ago and has since expanded into native ecosystems.

In Australia, Buffel grass was accidentally introduced by Afghan cameleers in the 1870s and it gradually naturalised in several areas in the north west of the country. The grass was intentionally introduced as a pastoral species in the 1920s (Centre for Arid Zone Research 2001; Friedel et al. 2007b; Smyth et al. 2009). It was first sown in Queensland in Cloncurry in 1926, then Rockhampton in 1928 (Humphreys 1967) and by the 1930s experimental sowing was made in several other Queensland districts (Hall 2000; Eyre et al. 2009). Around 1950-60, after a period of prolonged drought in central

Australia, Buffel was actively planted to prevent erosion and minimise dust storms around the airport at Alice Springs (-23.700297 S, 133.880510 E), where it has naturalised over the past 30 years (Centre for Arid Zone Research 2001; Cameron 2004). Concurrent with the introduction of the grass in central Australia, Australian pastoralists were importing new Buffel varieties from Northern Africa and India. These varieties displayed varying success in establishment depending on locality and climate (Friedel et al. 2007b). Buffel grass in its many forms now occupies extensive regions of the Australian mainland (Friedel et al. 2007b). It is the one of the most important pastoral species in Queensland, and covers vast expanses of native woodlands and grasslands (Cavaye 1991). In New South Wales, Buffel grass is adapted to more northern, arid parts of the state (NSW Department of Primary Industries 2004).

In the Americas, Buffel grass was first introduced to the USA in 1917 as a trial pasture species. Initial trials, located on the heavy clays of northern Texas failed (Hanselka 1988). Thirty years later, in 1947, it was grown successfully in lower brush country of San Antonio, Texas (Hanselka 1988). The variety, taken from the Turkana Desert of Northern Kenya, established readily from seed (Halvorson 2003) and by the 1950s when Texas was in its seventh year of drought, it became commercially available and flourished under the dry conditions (Hanselka 1988). By 1985 ranchers in southern Texas had established the grass over 4 million hectares of US farming land (Cox et al. 1988). The grass was introduced into Arizona by the US Soil Conservation Service in the 1940s and spread out from plantings by 1954. By the early 1980s, after several wet summers, it extensively naturalised in the Santa Rita Experimental Range of Tucson, Arizona (Halvorson 2003). In the 1970s or 80s it was discovered on the Organ Pipe Cactus National Monument (Rutman et al. 2002), an important site created to preserve a representative area of Arizona's Sonoran Desert. Buffel grass spread to cover as much as 625 square miles of the site by 1994 (Rutman et al. 2002). The grass was also introduced into the US state of Hawaii, where 33% of native grasslands were displaced by *Cenchrus* dominated grasslands within 30 years of its introduction to the island (Warren et al. 1993). Restoration of Hawaiian native grasslands has begun, and success has been demonstrated over a 4 year period (Daehler et al. 2005).

In the 1970s Buffel grass was introduced into Sonora, Mexico from the US to bolster the cattle industry (Cox et al. 1988; Franklin et al. 2006; De la Barrera et al. 2007). From 1973 to 2000 Buffel grass pastures in Mexico increased from 7,700ha to

140,000ha (Franklin et al. 2006). It is estimated to have the potential to cover 53% of Sonora and up to 12% of Mexico overall (Arriaga et al. 2004). The Mexican government promotes the use of Buffel grass, which is actively planted to this day (Lyons et al. 2009) and it is unlikely to regulate its spread because cattle ranching drives so much of the economy (Tix 2000).

In the 1950s Buffel grass was introduced into the Paraguayan Chaco, South America, from Texas. It was sown on a large scale for about 30 years until Buffel blight and other foliar diseases that attack the species were introduced (Glatzle 2003). The grass was difficult to establish on sandy soils in this region and since the 1980s it has been gradually replaced by Gatton panic *(Panicum maximum* Jacq.), another African perennial, which is easier to establish and harvest in this area (Glatzle 2003).

According to the Global Biodiversity Information Facility Buffel grass is also present in Central American countries Colombia, Nicaragua, El Salvador and Honduras as well as Brazil, Bolivia, French Guiana, Panama and Venezuela in South America and some Caribbean islands, although there is little documentation regarding its introduction to these locations (Global Biodiversity Information Facility 2011).

2.2 NOMENCLATURE AND MORPHOLOGY

Buffel grass (*Cenchrus ciliaris L.)* is a robust, deep-rooted C4 perennial tussock grass native to tropical and sub-tropical arid environments (Sharif-Zadeh et al. 2001). The species has highly varied morphological and physiological characteristics, which when combined with its wide geographic distribution, have led to considerable taxonomic uncertainty, with many synonyms evolving as a result **(**Table 1**)**. The common name *Buffel grass* is widely accepted and generally refers to *Cenchrus ciliaris* or *Pennisetum ciliare*. Adding uncertainty to any accounts of Buffel grass is that the genera *Cenchrus* and *Pennisetum* are not easily distinguishable, and caution should be taken to ensure that records of the species are credible (Pers. Comm. Helen Vonow, South Australian Herbarium).

Table 1 Buffel grass synonyms

Common	Buffel grass, African Fox-tail Anjan grass, koluk katai Buffel sandbur, Zacate buffel, pasto buffel
Scientific	*Cenchrus ciliaris, C. Setigerus* Vahl., *C. aequiglumis* Chiov., *C. anjana* Ham., *C. bulbosus* Fresen., *C. digynus* Ehrenb., *C. aequiglumis* Chiov., *C. anjana* Ham., Ex Wallich, *C. bulbosus* Fresen., *C. digynus* Ehrenb. Ex Boiss., *C. echinoids* Wight Ex Steud., *C. glaucus* Mudaliar & Sundaraj, *C. lappaceus* Tausch, *C. longifolius* Hochst. Ex Steud., *C. mutabilis* Wight ex Hook., *C. pennisetiformis* Hochst. & Steud., *C. pubescens* L. ex B.D. Jacks., *C. Rigidifolius*, *Pennisetum ciliare, P. cenchroides* Rich. ex Pers., *P. distylum* Guss., *P. incomptum* Nees ex Steud., *P. longifolium* Fenzl ex Steud., *P. petraeum* Steud., *P. polycladum* Chiov., *P. prieurii* A. Chev., *P. rangei* Mez, *P. rufescens* (Desf.) Spreng., *P. rufescens* Hochst. ex Steud., *P. teneriffae* Steud (Tu 2002)

Morphological and physiological differences between Buffel grass varieties have been studied on several occasions (Jacobs et al. 2004; Mnif et al. 2005a; Jorge et al. 2008; Morales-Romero et al. 2008; Gutierrez-Ozuna et al. 2009). These studies describe the range of dimensions to which the grass grows (Table 2). A Pakistani study on the morpho-genetic variability between 20 Buffel grass accessions (Arshad et al. 2007) showed that most (38.7 %) of the morphological variance between accessions used in the study were associated with the height of the plant, leaf area, number of leaves on the main tiller, part of internodes covered by leaf sheath, the number of branches per plant and the number of reproductive branches per plant (Arshad et al. 2007).

Table 2 Approximate range of dimensions of Buffel grass morphology as described in the literature.

Trait	**Dimensions**
Plant height	20 - 150 cm
Stem thickness	1 - 3 mm
Leaf	1.5 - 30 cm long, 3 - 8 mm wide
Ligules	0.5 - 2 mm
Inflorescences	Yellow - purple - grey
Time to flowering	Approximately 3 months from germination
Roots	Up to 2.4 m deep

Intra-species variation has arisen both naturally and from the commercial development of new strains to improve productivity of pastoral land. Cultivars have been developed with increased growth rates, disease resistance and tolerance to a range of environmental conditions. Consequently, knowledge about the suitability of various strains in different environments may be critical for effective control of infestations. The provenance, exotic distribution, conditions for growth and characteristic traits of some commonly sown *Cenchrus ciliaris* cultivars are therefore presented in Table 3.

Commercial cultivars may be grouped into tall, medium and short varieties. Tall varieties (growing up to 1.5 m) are suited to heavier soils and higher rainfall and are generally used for cattle production. These usually display bluish-green coloured leaves, and develop rhizomes. Smaller varieties (< 90cm), generally used for sheep production and erosion control, are typically suited to lighter textured soils, are less tolerant of flooding, and have poor rhizome development **(**Table 3**)**.

Generally, Buffel grass is apomictic (Bray 1978), although rare sexual individuals have been identified (Akiyama et al. 2005). Seed spreads easily by wind, along water courses and human or animal traffic. Some varieties can also reproduce vegetatively through rhizomes and stolons. The result of this is that a range of plant forms occur and can be observed growing in dense monotypic stands, as well as in small clumps or even lone tussocks throughout the landscape.

To thoroughly assess the threats posed by Buffel grass invasion, we must ask whether the invasive capacity also varies between sub-species. This has been studied in Mexico (Gutierrez-Ozuna et al. 2009) and Tunisia (Mnif et al. 2005b). Both studies concluded that invasion success is not directly linked to genotypic variation, and that other factors such as phenotypic plasticity and propagule pressure could be major determinants of the invasion success of Buffel grass. However, Humphreys (1967) reports that shorter Buffel varieties are less competitive against native grasses than taller Buffel varieties in sub-tropical climates, and may be better suited to semi-arid conditions. Further research is required for a conclusive answer to this question (Humphreys 1967).

Table 3 The provenance, exotic distribution, conditions for growth, and characteristic traits of some commonly sown *Cenchrus ciliaris* cultivars (Food and Agriculture Organization of the United Nations, 2011)

Height	Cultivar/ Variety	Provenance	Exotic distribution	Environmental tolerances	Characteristic traits	Rhizomes
Tall	Biloela	Dodoma in Tanzania 1937 (CSIRO)	Rockhampton, Queensland Australia	Tolerant of flooding (more so than shorter varieties) Suited to a range of soils, can survive on heavier clays Suited to higher rainfall High salt tolerance (Griffa, Ribotta et al. 2010)	Straw coloured seed head with red tinge	Yes
Tall	Boorara A-12a-3	Kenya	Cattle ranch in central Queensland	Will grow in infertile soils Suited to higher rainfall		Yes
Tall	Nunbank A-12a-5			Suited to higher rainfall		Yes
Tall	Bella		Australia	Suited to higher rainfall	Good resistance to Buffel Blight	Yes
Tall	Viva		Australia	Suited to higher rainfall	Good resistance to Buffel Blight	Yes
Tall	Tarewinnabar	Kenya	Queensland	Greater frost tolerance than other cultivars (exp. Molopo)	Scarce seed production	Yes
Tall	Molopo A-12a-2	Molopo River, Western Transvaal, South Africa	NSW	Good frost tolerance More tolerant of flooding than sorter varieties	Low seed production,	Yes, good development
Tall	Lawes	Pretoria, Africa			Identical to American cultivar T3782, blue Buffel and Molopo	Commercial seed N/A
Tall	Zeerust			500-625mm rainfall area in Africa	Tall, leafy	
Height	**Cultivar/ Variety**	**Provenance**	**Exotic distribution**	**Environmental tolerances**	**Characteristic traits**	**Rhizomes**

Tall	Edwards	Kenya	Several hybrids being tested in the US and Australia	Withstands heavy grazing	Robust habit, , minimal seed	
Medium	G636 Kongwa 531	Kongwa, Tanzania		Best results on red Barth veiled at Kongwa, Tanzania under annual rainfall 561mm	Fine leaved, erect, ample seed,	
Short-medium (90cm)	Gayndah, CPI73386, A-12a-7	Kenya	Australia		Short, suitable for sheep grazing Leafier and more tillers than other cultivars (Cameron 2004) Straw coloured seed head (Qld Primary Industries and Fisheries 2010)	No
-	Chipinga	Zimbabwe			Fine leafy variety	
Short	American A-12a-9	American	Australia	Suitable for sheep but its high palatability may lead to its overgrazing and disappearance High salt tolerance (Griffa, Ribotta et al 2010)	Identical to American material T.4464, Leafier and more tillers than other cultivars (Cameron 2004) Red to purple coloured seed head	No
Short	Higgins	Texas			True breeding apomictic variety developed from a sexual variety	
Short	West Australian A-12a-8	Afghanistan	1870-80 Australia on Afghan cameleers	Least drought tolerant of all, nutritionally valuable Grows well on cleared gidgee in Queensland	High shoot/ root ratio, increased by phosphorus application (Humphreys 1967)	
Dwarf	Manzimnyarna and Sebungwe	Semi-arid conditions in Africa				

2.3 ESTABLISHMENT AND GROWTH

Understanding requirements for germination, growth and development is important for identifying fundamental habitat requirements of a species. In arid landscapes, the most critical life history stages in the development of any plant community are seed germination and seedling emergence (Call et al. 1991). There have been numerous studies of the seed longevity and germination rates of Buffel grass, due to its popularity as a pasture species (Winkworth 1971; Sharif-Zadeh et al. 2001; Bhattarai et al. 2008). In this section we explore some of the key findings from these studies.

Soil moisture is critical for germination (Winkworth 1971; Ward et al. 2006). For Buffel grass, the minimum rainfall for seedlings to emerge from loam soils is 6.3mm (3.14mm on two consecutive days). This was determined by Ward et al. (2006) in a greenhouse experiment designed to simulate conditions during the summer rainy season of Tucson, Arizona where Buffel grass is prevalent. They found that the probability of new emergence was highest on days 3 and 4 for seedlings that received 3 and 4 consecutive days of simulated precipitation. Probability for new emergence dropped substantially after day four. Based on the results from this experiment Wart et al (2006) determined that conditions required for emergence of 50% viable Buffel grass had occurred in Tucson in 1 of 2 years over the summer rainy season. In central Australia periods suitable for perennial grasses to germinate are suggested to occur about once a year on average (Winkworth 1971).

Buffel grass withstands infrequent germination opportunities, in part due to the extreme longevity of its seed bank, estimates of which range from 2 to 30 years (Friedel et al. 2007a). Seeds may lay dormant in the ground for up to 8 months, while retaining the original seed viability (Winkworth 1963). Beyond 12 months, germination rates drop to less than 12%, and remain at 10% for around a two years after that (Winkworth 1963).

Buffel seed has been shown to germinate between 10 - 40 °C with optimal germination rates at 30 °C / 20 °C day/ night temperatures. These figures were obtained in continuous light, continuous dark and for light/ dark alterations (Winkworth 1971). Germination is influenced by substrate, with the highest germination rates in potting mix, followed by clay followed by paper towelling in study of germination in these three substrates (Bhattarai et al. 2008).

Buffel grass appears to perform particularly well at elevated CO_2 levels and it demonstrates increased biomass, plant height, leaf length, leaf width and improved overall growth performance, as is usual for tropical C4 grasses (Bhatt et al. 2007). CO_2 uptake and water use efficiency of the plant, are greatest at day/ night air temperatures 30/20 °C and decrease at higher temperatures until death at 45/35 °C day/night temperatures (De la Barrera et al. 2007). The optimum temperature for photosynthesis is 35°C (Tix 2000) . The species is drought resistant (Phillips 1931) and does not tolerate extended periods of flooding or subfreezing temperatures (Lazarides et al. 1997; Arizona-Sonora Desert Museum Staff and Volunteers 2008). Buffel grass can tolerate soils with low levels of nutrients. However, it does show increased water use efficiency (WUE), crude protein and dry forage yields with increased nitrogen (Patidar et al. 2008) and widened shoot/root ratio with increased phosphorus (Humphreys 1967; Christie 1974). Buffel grass has a moderate salt tolerance: the varieties Americana and Biloela have higher salt tolerance than other cultivars (Griffa et al. 2010).

2.4 ADAPTATIONS AND ENVIRONMENTAL CONSTRAINTS IN ARID ECOSYSTEMS

C4 grasses, such as Buffel grass, typically dominate tropical savannahs, a biome characterised by a summer growing season (when high temperatures coincide with high rainfall), open-canopies, and dense grassy understoreys that fuel frequent fires. By contrast, arid and semi-arid ecosystems are characterised by low, erratic and infrequent rainfall events, high evapo-transpiration rates and sparse vegetation due to insufficient soil moisture to promote seedling emergence and further plant growth (Reynolds et al. 2004). Consequently, arid systems are relatively resistant to alien invasions (Usher 1988). Yet, Buffel grass thrives in them.

Buffel grass demonstrates several qualities that make it uniquely suited to survive harsh arid conditions. These include the accumulation of carbohydrates at the base of its stems for slow release when needed, a deep root system (up to 2.5 m in deep soils) (Halvorson 2003) that enables it to access water supplies faster and for longer than most native herbs and forbs, as well as extended seed longevity and opportunistic germination (Winkworth 1971; Centre for Arid Zone Research 2001; Sharif-Zadeh et al. 2001). Additionally, arid environments may present Buffel grass with less competition, disease and predation. For example, in most cases, anecdotal evidence indicates that Buffel grass, by virtue of its presence, outcompetes native plants for water, light and nutrients. However, it can struggle for dominance against other exotic grasses of similar provenances such as the such as Parthenium weed *(Parthenium hysterophorus*), native to subtropical North and South America (NSW Department of Primary Industries 2004). Furthermore, in arid climates, Buffel grass may be less affected by tropical diseases including Buffel Blight *(Magnaporte grisea)*, Ergot, Smut, Rust, and Blast and the Paralid moth, which help to suppress the species in the tropics (NSW Department of Primary Industries 2004; Qld Primary Industries and Fisheries 2010; Food and Agriculture Organization of the United Nations 2011).

A recent study identified effective rainfall and rainfall seasonality as the most significant factors influencing the distribution of savannahs at a global scale (Lehmann et al. 2011). At a regional scale, the researchers explore how topography, soils and disturbance interact with rainfall to impact woody vegetation growth and fire frequency, which reduce and promote the growth of C4 grasses, respectively. They conclude that woody vegetation growth should be considered as a potential surrogate for identifying the potential limits of the savannah biome (Lehmann et al. 2011).

Here, we review the factors that promote and constrain the geographic extent of Buffel grass distribution. We report on the four factors identified as key distribution determinants of C4 grasses worldwide: climate, edaphic characteristics, topography and fire / disturbance. We acknowledge that due to large intra-species variation there may be some differences in apparent environmental tolerances of the grass; however our discussion refers to the species as a whole. Specific climate and landscape features that are reported to influence Buffel grass distribution are summarised in Table 4.

Table 4 Summary of the landscape features that may influence Buffel grass distribution

Environmental factor		Location, Climate	Comment	Reference
Climate	Temperature	Semi-arid Queensland, Australia	30 degrees Celsius optimum in the region for Buffel grass growth	(Christie 1975)
		Kenya, Southern Africa, Southern Texas, Mexico, and Australia	Survives at minimum annual average temperatures of between 5 and 25°C	(Cox et al. 1988)
	Rainfall	Central Australia	Buffel grass abundance higher after summer rains than winter rains	(Clarke et al. 2005)
		Mexico	Predicted distribution is between 0-800mm annual rainfall	(Arriaga et al. 2004)
		Kenya, Southern Africa, Southern Texas, Mexico, and Australia	0-800mm annual rainfall	(Cox et al. 1988)
	Illuminance	Semi-arid Queensland, Australia	Small effect on the growth of Buffel grass	(Christie 1975)
Geology and Soils	Soil texture and fertility – increased phosphorus and pH		Affects the efficacy of Buffel grass spread into adjacent ecosystems	(Eyre et al. 2009)
	Phosphorus	Central Australia	High P levels results in high Buffel grass growth	(Winkworth 1964; Humphreys 1967; Christie 1974)
	Soil water potential	Semi-arid Queensland, Australia		(Christie 1975)
	Soil mineral deficiency	Central Australia	May be a limiting factor	(Winkworth 1964)
	Soil type	Arizona, USA and Sonora, Mexico	Buffel grass appears to grow mainly on soils derived from volcanic, gneissic and limestone where chemistry and mineralogy vary greatly	(Van Devender et al. 2006)
	Soil texture	Kenya, Southern Africa, Southern Texas, Mexico, and Australia	Buffel grass persists well in well drained loam, sandy loam, clay loam and sandy clay loam soils, and will lose vigour and die when established in silt, silt loam, silty clay loam, silt clay and clay soils	(Humphreys 1967; Cox et al. 1988; Van Devender et al. 2006)

	Environmental factor	Location, Climate	Comment	Reference
Topography, land systems and vegetation associations	Woody vegetation	Poplar box community, Queensland, Australia	Higher retained vegetation, lower Buffel grass, suggested as result of propagule pressure, competitive capacity of BG	(Eyre et al. 2009)
	Leaf litter	Queensland Eucalypt woodlands, Australia	Higher leaf litter, lower BG	
	Ground cover		Buffel grass readily colonises	
	Modified landscapes	Central Australia	Buffel grass can be observed more frequently and at higher densities in modified landscapes	
	Vegetation type	Mexico	Desert scrub most at risk of invasion, followed by Mesquite woodlands, Abandoned agricultural land and Tropical deciduous forests	(Arriaga et al. 2004)
	Elevation		Potential distribution ranges from sea level to 900m ASL.	
	Aspect	Arizona, USA and Sonora, Mexico	Hillside concentrations of Buffel grass are typically found on steeper south, south-east and south-west aspects	(Van Devender et al. 2006)
	Slope	North eastern Sonora	Correlated with slopes of 14-19 degrees on relict clay soils	
	Creek lines (Red gum)	Central Australia	50 samples, 72% Buffel grass	(Clarke et al. 2005)
	Creek lines (Tea tree)		75 samples, 81% Buffel grass	
	Saline alluvial flats		100 samples, 63% Buffel grass	
	Iron wood alluvial flats		250 samples 62% Buffel grass	
	Mulga rises		124 samples, 22% Buffel grass	
	Drainage systems, alluvial plains	Central Australia arid climate		(Eyre et al. 2009)
Disturbance Zones	Stocking routes and grazed sites	Queensland Eucalypt woodlands, Australia	Highest mean Buffel grass cover on stocking routes, compared to national parks and state forest where it is not detected Higher Buffel grass cover where grazing occurs	(Eyre et al. 2009)
	Burnt sites	Queensland Eucalypt woodlands, Australia	Buffel grass abundance highest on site that experience “low intensity fire” as compared to “high intensity fire” or no fire.	
	General	Mexico	Disturbance increases the chances of Buffel grass colonizing a site and becoming invasive	(Arriaga et al. 2004)
	Roads and highways	Arizona, USA and Sonora, Mexico	Buffel grass range expands along major freeways, especially on those that have been repeatedly bladed	(Van Devender et al. 2006)

2.4.1 Climate

Buffel grass occupies a diverse range of climates. It can tolerate extremely high temperatures approaching 50 °C (De la Barrera et al. 2007), but it will not establish where the mean annual minimum drops to below 5 °C (Cox et al. 1988). It tolerates wide ranging annual rainfall averages, establishing in regions that receive anywhere from less than 250mm to 2670mm of rainfall, annually (Tix 2000; NSW Department of Primary Industries 2004). Temperature appears to be a stronger limiting factor to the species global extent than annual average rainfall. However, it has been observed that episodic advances in invasion fronts typically follow early summer rainfall events (Friedel et al. 2006; Mnif et al. 2010).

Rainfall seasonality is a key factor influencing the distribution of the savannah biome worldwide (Lehmann et al. 2011). Savannah, categorised as a habitat with a C4 grass layer, such as Buffel grass, shows the greatest response to summer rainfall. In sub-tropical parts of Queensland, Australia, for example, Buffel grass is primarily sown in areas where 60% of annual rainfall reliably occurs during the summer months. However, rainfall seasonality is linked to the probability of drought, tree survival, woody vegetation growth rates and thus the probability of disturbance; therefore its influence on Buffel grass distribution should not be considered in isolation from these factors.

Aside from rainfall seasonality, another limiting factor is effective rainfall (Lehmann et al. 2011). Effective rainfall is the amount of rainfall available for plant uptake, and is influenced by a range of factors such as temperature, soil and topography. Effective rainfall is particularly important where rainfall is infrequent or erratic, such as in arid environments (Lehmann et al. 2011).

2.4.2 Edaphic characteristics

Buffel grass grows on a wide range of soil types but long term persistence appears to be dependent on specific textural types (Cox et al. 1988). For instance, seedlings emerge in sandy, silty and clayey soils, but emergence declines as either sand, silt or clay content approach 100% (Cox et al. 1988). Meanwhile, they gradually lose vigour and die when established in silt, silt loam, silty clay loam, silt clay and clay soils (Cox et al. 1988). It persists in well drained loam, sandy loam, clay loam and sandy clay loam soils and actively spreads by seed in north west Australia in sandy loam soils (Humphreys 1967). The grass prefers sandy and sandy loam soils (Centre for Arid Zone Research 2001; Van Devender et al. 2006) but will colonise loam soils, provided it experiences approximately 90 days growth in the summer and relatively warm, dry winters (Cox et al. 1988).

The importance of soil texture on plant growth is typically linked to the capacity of the soil to retain moisture (Reynolds et al. 2004). Several Buffel cultivars have been developed to withstand flooding, and thus are more likely to be able to establish on heavier soils which retain moisture. In dry areas Buffel grass will adapt to heavy clay soils that become too water-logged in tropical regions (Cameron 2004). It is generally slow to establish on black cracking clay, but does well once established (Food and Agriculture Organization of the United Nations 2011). More rhizomatous varieties are believed to show superior adaptation to heavier soils (Humphreys 1967).

In the Sonoran Desert of Mexico, Buffel grass distribution is limited to a few well defined geomorphic settings (Van Devender et al. 2006). It occurs on soils derived from volcanic deposits (rhyolite and basalt), gneiss (granite) and limestone, where soil chemistry and mineralogy vary greatly, thus its distribution does not relate in any simple way with standard soil types (Van Devender et al. 2006). The species preference for soils derived from volcanic deposits is also observed in the MacDonnell Ranges of central Australia where Buffel grass readily grows on granitic geomorphic settings and is absent from adjacent quartzite and sandstones (Pers. Comm., Peter Latz). In southern Queensland soils most suitable for Buffel grass establishment include red earths with friable surface (ironbark and poplar box country), Lighter Brigalow and Brigalow /Belah clays, sandy soils with moderate phosphorus (river frontage sands and some Cypress pine country), as well as, soil once under gidgee or softwood scrub (Cavaye 1991). The observation that Buffel grass growth is strong on red earths (Cavaye 1991) should be noted with caution, for in central Australia, Buffel grass only grows on red earths in localised depressions (Pers. Comm., Peter Latz).

The species can establish on soils of low fertility, provided nitrogen and phosphorus are sufficient (Bhati et al. 1984). Several studies illustrate that a high level of phosphorus in particular results in greater Buffel grass yield (Winkworth 1964; Humphreys 1967). The importance of soil fertility may vary with respect to rainfall

(Lehmann et al. 2011), and in arid locations soil of high fertility may be especially important for Buffel grass to establish. Buffel grass is intolerant of high levels of available soil aluminium and manganese (Spain and Andrew (1977)[1], as cited in (Cook 2007)). According to a study conducted in Tanzania, the seed spreads well in soils with a soil pH ranging from 7-8 (Brzostowski (1962)[2] as cited in (Food and Agriculture Organization of the United Nations 2011)).

2.4.3 Topography, land systems & vegetation associations

Buffel grass distribution can range from sea level to 2000m in altitude (Global Biodiversity Information Facility 2011). At a local scale, the grass tends to establish in natural depressions across the landscape. This is particularly true in arid environments, as depressions provide a moist environment for establishment as well as protection from grazing (Qld Primary Industries and Fisheries 2010). In arid Australia, Buffel grass often displays strongest growth along creek lines and embankments (Centre for Arid Zone Research 2001). This is consistent with global observations that river systems are a major means for the spread of weeds (Johansson et al. 1996).

On the Plains of Sonora the species exists in large areas that are flat and also up adjacent slopes. On slopes the distribution is tightly correlated to slope angles of 14 to 19 degrees with relict clay soils, and can be absent from nearby slopes with different conditions of rock cover, depth to hardpan and slope angle (Van Devender et al. 2006). The grass is less common on gently sloping bajadas of Sonora where it tends to clump in the shade of trees, larger shrubs and prickly pears (Van Devender et al. 2006). Conversely, at a broad scale, C4 species tend to flourish in open environments where ample light is available, and are physiologically incapable of dominating closed-canopy ecosystems (Sage et al. 2003).

In the MacDonnell Ranges of central Australia Buffel grass is prevalent on the low-lying, rich soils of the alluvial plains beneath ironwood and fork-leaved corkwood trees. It can also be seen growing throughout rocky granitic hills, beneath *Acacia* open woodlands, yet it can be completely absent from adjacent outcrops of alkaline dolomite

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[1] Original source unobtainable

[2] Original source unobtainable

or amphibolite that support hummock grassland communities of native C4 grass, *Triodia* (Pers. Comm., Peter Latz).

2.4.4 Fire and other disturbances

Disturbance has long been recognised as a facilitator for the spread of invasive species (Lonsdale 1999). Disturbance, causing soil surfaces to loosen, may be natural or anthropogenic in nature. Commonly, anthropogenic causes include human road and foot traffic. For instance, Buffel grass often establishes along disturbed rights of way such as highways and larger paved roads that have been repeatedly bladed (Van Devender et al. 2006). Natural disturbances may relate to occurrences such as the upturn of sediments along watercourses, wildfire and the movement of animals, reptiles or birds. Establishment of the species has been associated with burrowing animals such as endangered Australian marsupial, the Northern Hairy-nosed Wombat *(Lasiorhinus kreftii)*, and the European Rabbit *(Oryctolagus cuniculus)*, which is a significant pest in arid regions of Australia (Department of the Environment Water Heritage and the Arts 2009).

Perhaps the most damaging act of disturbance is fire. Buffel grass produces a high fuel load that supports more frequent and intense fires than arid landscapes are otherwise likely to be exposed to (D'Antonio et al. 1992). It is often first to remerge on ash beds, hence forming a positive feedback loop which favours its own regeneration, and modifies the invaded system irreversibly (Miller et al. 2010). There are several physiological characteristics of Buffel grass that enable it to respond so quickly to fire and rain, including a deep penetrating root system, and a long lifespan of individual tussocks, which mean that it can re-sprout from established tussocks following fire. There is some evidence to suggest that the more severe the fire, the more rapid the post-fire recovery of above ground biomass (Miller et al. 2010), with one study suggesting that Buffel grass cover doubles after fire (Butler et al. 2003). The degree of disturbance necessary for establishment may be closely linked to the competitive situation of the surrounding flora (Humphreys 1967). Fire immediately reduces competition with surrounding vegetation, and hinders recruitment of juvenile woody vegetation, preventing future recovery of the landscape and making it more vulnerable to rapid colonisation by fast growing species such as Buffel grass. Fire also temporarily increases available phosphorus in the soil (Bennett et al. 2003) which Buffel grass may be able to rapidly exploit (Miller et al. 2010).

We have observed that once established Buffel grass may not require disturbance to spread and consider that rhizomes may be an agent for this, though further research is required to confirm this.

2.5 IMPACTS ON ECOSYSTEM FUNCTION AND BIODIVERSITY

Invasive species are recognised as the primary cause of global biodiversity loss, homogenising the world’s flora and fauna (Ustin et al. 2002). Grass invasions can be particularly devastating, impacting ecological organisation of populations to ecosystems, and in their aggregate may be sufficiently widespread to alter global aspects of ecosystem function (D'Antonio et al. 1992). Buffel grass is no exception.

Buffel grass invasion can devastate local ecosystems by altering wildfire regimes, soil erosion rates, ground surface temperatures and supply of vital resources to surrounding life forms, compromising biodiversity (D'Antonio et al. 1992). Significant invasions have been reported in arid communities throughout Australia, the USA, Mexico and South America and many species and ecosystem functions have been impacted (Table 5**)**.

Several studies illustrate a negative relationship between Buffel grass occurrence and general species richness (Collins et al. 1991; Bestelmeyer et al. 1999; Fairfax et al. 2000; Blanco et al. 2005; Clarke et al. 2005; Jackson 2005; Flanders et al. 2006; Franklin et al. 2006; Hannah et al. 2007). Clarke *et al* (2005) conducted an important investigation into the long term changes in semi-arid vegetation of central Australia, which demonstrated that Buffel grass had a more significant impact on herbaceous species richness than rainfall variability.

Flora and fauna impacted by Buffel grass are summarised in Table 5. Most of these examples are reported in grey literature and further research is needed in order to conclusively link Buffel grass to loss of particular species. Included in the list are keystone species the Saguaro Cactus (Schiermeier 2005) and the River Red Gum (Centre for Arid Zone Research 2001) which characterize the deserts of Arizona and Australia, respectively. Species such as the Saguaro Cactus, the River Red Gum and other woody perennials do not withstand repeated fires as they have slow juvenile recruitment compared with Buffel grass.

Table 5 Flora and fauna impacted by the introduction of Buffel grass to their native habitats

Species/ community; Location	**Observed impact of Buffel grass invasion on named species**	**Reference**
River Red Gum (*Eucalyptus camaldulensis Dehnh*); Australia	BG growing in creek lines where River Red Gums are found – withstands hot fires in winter and spring that RRG may not recover from	(Centre for Arid Zone Research 2001)
Mulga *(Acacia aneura);* Australia	More frequent wildfires, reducing numbers in just decades	
Northern Hairy-nosed wombat *(Lasiorhinus krefftii);* Queensland, Australia	Disturbed soils around burrow promote/ facilitate Buffel grass establishment displacing native grasses and forcing the burrow occupant to travel further to feed	(Centre for Arid Zone Research 2001; Friedel et al. 2007a)
Pili grass (*Heteropogon contortus*); Hawaii, USA	One of several non-indigenous grasses displacing Pili grass in most dry, leeward habitats of the Hawaiian Islands	(Daehler et al. 2005)
Various endemic species; Australia	Buffel grass is displacing native species from mesic islands in arid ecosystems	(Humphreys 1967)
Species richness	Declines in the presence of Buffel grass	(Butler et al. 2003; Clarke et al. 2005; Jackson 2005)
Ground dwelling bird guilds and “hot climate specialist” ants; central Australia	Composition of guilds/ community groups varies	(Smyth et al. 2009)
Various reptiles; Queensland, Australia	Both increaser and decreaser responses to Buffel grass presence	(Eyre et al. 2009)
Forbs; Queensland, Australia	Minimally effected by Buffel grass, but may be due to low rainfall at time of experiment	(Eyre et al. 2009)
Various native grasses, Australia	Winter growth is reduced when competing with Buffel grass	(Clarke et al. 2005; Eyre et al. 2009)
Various herbaceous species; Australia	Buffel grass leachates shown to reduce seed germination of various Australian herbaceous species under laboratory conditions	(Eyre et al. 2009)
Forbs (*Cyperus* gracilis, and *Radscondons*), Australia	10% less abundant in Buffel grass pasture	
Many-headed Wiregrass(*Aristida caput-medusae*), Slender Chloris (*Chloris divaricata*), Fairy grass (*Sporobulus caroli*)	Increaser response to Buffel grass infestation	
Cryptoblephaus pannous	Decreaser response to Buffel grass infestation	

Species/ community; Location	**Observed impact of Buffel grass invasion on named species**	**Reference**
Trees, Peachwood shrub, False Sandalwood *(Eremophila mitchellii); Australia*	Following exposure to Buffel grass fuelled fire Tree canopy shows recovery in the form of epicormic shoots, Peachwood resprouts but does not fare so well as neighbouring trees, False Sandalwood did not re sprout	(Butler et al. 2003)
Short-lived forbes, suffruticose shrubs,	More abundant when Buffel grass is present	(Clarke et al. 2005)
Woody layer	Negatively affected by Buffel grass fuelled fires	(Clarke et al. 2005)
Desert tortoise (*Gopherus agassizii*) and Mule deer (*Odocoileus hemionus*) ; Sonoran Desert Ecoregion	Habitat is threatened by Buffel grass fuelled fires	(Volunteers. 2008)
Giant Saguaro Cactus *(Carnegiea gigantea)*; Arizona and Texas, USA and Mexico	Species devastated by Buffel grass fuelled fires, and competition for water	(Schiermeier 2005; Volunteers. 2008)
Cactus ferruginous pygmy owl (*Glaucidium brasilianum cactorum*); Arizona, USA	Threatened as a result of Buffel grass fuelled fires devastating cacti in which the pygmy owl lives	(Defenders of Wildlife 2011)
Columnar cactus (Pachycereus pectin-aboriginum); Sonora, Mexico	Growth examined in thorn scrub and in Buffel grass pastures – no significant effect on plant abundance but a major difference on size distribution. All seedlings that emerged on pasture died within one year. Data shows that adult populations persist but cannot replace and will face local extinction	(Morales-Romero et al. 2008)

Buffel grass produces large volumes of standing dead matter which burns hotter and faster than most grasses native to Australia and the Americas (D'Antonio et al. 1992; Martin-R et al. 1999; Schiermeier 2005; Smyth et al. 2009). The result is increased wildfire frequency and intensity in ecosystems not adapted to fire. Additionally, it regenerates quicker than many natives on ash beds, creating a positive feedback loop that favours Buffel grass regeneration (D'Antonio et al. 1992; Miller et al. 2010). An alarming aspect of Buffel grass invasions is that they can occur quite suddenly. Areas apparently devoid of Buffel grass may be rapidly dominated by the species following the rains that trail a period of prolonged drought or fire, with this dominance often maintained for decades (Clarke et al. 2005).

The impact of Buffel grass on arid ecosystem function is significant. This is because creek lines typically act as a blockade to the spread of fire, even when dry, because the soils lining the creek do not support the growth of dense, fire-fuelling grasses. Anecdotal evidence indicates that Buffel grass thrives along creek lines in dry environments (Miller et al. 2010). Thus, a feature that should prevent the spread of fire can transport it, effectively acting as the “wick for the fire” (Humphries et al. (1992) as cited in (D'Antonio et al. 1992)) and the fear, however sensationalised, is that Buffel grass will transform arid environments such as the Sonora Desert into African-style savannahs.

The overall impact of Buffel grass invasions on biodiversity is not fully known, although it is likely that we are seeing only the beginning of its potential to encroach into new ecosystems. The extent of Buffel grass invasions will continue to expand until new equilibriums have been reached within invaded ecosystems (Dullinger et al. 2009).

2.5.1 Is Buffel grass a true “invader”?

The apparent dependence of Buffel grass establishment on disturbed soil surfaces makes its ecological label as an “invader” controversial. Invasive species are considered such when they can successfully establish, become naturalised and spread to new natural habitats apparently without further assistance from humans and are generally new introductions into an eco-region (Radosevich et al. 2007). So, the question becomes whether Buffel grass could expand its range without human disturbance. One example that suggests it cannot is that of the Centro Ecologico de Sonora housing development in

Mexico. Environmental conditions in the region are and always were suitable for Buffel grass, yet establishment in the area was triggered only by major disturbances caused during the development of the new housing project (De la Barrera 2008). McIvor (2003) also attempted to answer our question, and concluded that while Buffel grass is able to colonise bare areas it is not able to invade dense vegetation suggesting it is not invasive (McIvor 2003). Whether Buffel grass behaves as a *true* invader appears to depend on different environmental factors. In Australia, Buffel grass displays the characteristics of both invaders and colonisers; in the tropical north of the Northern Territory (the "Top End") Buffel grass spreads from sown pastures either slowly or not at all. Conversely, in central Australia and western Queensland it spreads readily (Cameron 2004). This may relate to the nature of soil surfaces or soil type; Top End soils form a crust following rain that prevents seedlings from establishing, while soils of the arid inlands possess the crumbly/ loose surfaces required for Buffel grass establishment (Cameron 2004).

Overall, there is consensus in the literature that disturbances facilitate the establishment of the species and human are a frequent cause of disturbances. However, there is little evidence from the literature that human disturbances are necessary to facilitate spread at broad scales and once established, anecdotal evidence indicates that the species can often invade into adjacent areas unaided.

2.6 MANAGEMENT

Management of Buffel grass throughout invaded environments is crucial to conserve natural ecosystem structure, composition and function. Due to the many benefits of its cultivation, eradication of Buffel is not desired, nor is it likely that it could be achieved due to the extent of invasion. Therefore, control of invasions is conducted at a local scale. At present, there are several options for control of Buffel grass in infested land systems, including the application of herbicides, manual removal, prescribed burning and controlled animal grazing. Chemical controls can be effective, but application must be strategically timed to coincide with the species' period of peak growth (Dixon et al. 2002; Daehler et al. 2005; Johnson et al. 2008; Volunteers. 2008). Manual methods of control are costly, time consuming and therefore restricted to local removal efforts. To be effective, the entire plant must be removed; mowing is not effective. Prescribed burning followed by the application of herbicides and sowing of native grasses has been highly effective at suppressing Buffel grass while promoting the regeneration of native flora (Daehler et al. 2005). Additionally, while not the desired control mechanism from an environmental point of view, grazing can be effective at controlling the spread of Buffel grass (Pers. Comm. Peter Latz). Of course, economic and ecological analysis of the process of eradicating or controlling invasive species indicates that the most cost-effective and least environmentally damaging method is spread *prevention*.

2.7 CONCLUSIONS

Buffel grass (*Cenchrus ciliaris L.*) is grown widely in tropical and sub-tropical arid rangelands around the globe because of its high drought tolerance and capacity to withstand heavy grazing. However, in certain situations, particularly in arid to semi-arid environments, Buffel grass has the ability to rapidly invade the surrounding environment. Consequences of invasion can be significant as Buffel grass alters wildfire regimes and displaces native flora and fauna. Effective, strategic control of Buffel grass invasions requires knowledge of regions infested with or vulnerable to invasion, as well as a willingness of the community to be involved in its control.

At a global scale, temperature emerges as the primary factor restricting spread, with the species not surviving at average monthly temperatures below 5 °C (Cox et al. 1988). Rainfall seasonality and effective rainfall are influential, and a consistent summer rainy season is particularly important for growth. However, these factors can not be considered in isolation from variables such as vegetation and topography. Seedling emergence is reliant on soil disturbance. Consequently, the species regional distribution is likely to coincide with disturbed environments such as creek lines and roadsides. Soil texture influences germination rates and establishment. Once established it may be less selective with regard to soils. Successful population establishment may depend on appropriate soil moisture, soil texture, phosphorus/ nitrogen availability, topography and sun exposure. Phosphorus deficiency in soils is a particularly strong barrier to establishment in arid locations.

Arid and semi-arid environments are particularly prone to Buffel grass invasion and do not tolerate the increased frequency and intensity of wildfires that accompany increased biomass of the grass. Buffel grass fuelled fires are believed to be responsible for declining numbers of characteristic arid zone plants, the Saguaro Cactus (Arizona, USA) and River Red Gum (Australia). Arid landscapes worldwide stand out as requiring urgent control of Buffel grass.

Effective control of Buffel grass populations will require global action at local and regional scales. This paper has highlighted the morphological characteristics, environmental tolerances and biodiversity impacts of Buffel grass to facilitate predictive habitat modelling and identification of regions requiring urgent control as well as raise concern for control of this invasive weed.

2.8 ACKNOWLEDGEMENTS

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Chapter Three

Buffel grass roadside survey and invasive species distribution modelling

Marshall, V.M, Lewis, M., Ostendorf, B., Tuke, J. (2013) "Buffel grass roadside survey and invasive species distribution modelling" (Under revision)

Key words: invasive weed, Australia, roadside survey data, Buffel grass management, buffelgrass

Marshall, V.M., Lewis, M., Ostendorf, B. & Tuke, J. (2013) Buffel grass roadside survey and invasive species distribution modelling.
Invasive Plant Science and Management, (under revision).

NOTE:
This publication is included on pages 47-74 in the print copy of the thesis held in the University of Adelaide Library.

Chapter Four

Investigating multispectral imagery for detection of Buffel grass *(Cenchrus ciliaris)* infestations in central Australia

Article presenting aspects of this chapter was submitted to the XXII International Symposium of Photogrammetry and Remote Sensing (Melbourne, Aug. 25th – Sept. 1st 2012) and is accessible via http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XXXIX-B8/277/2012/isprsarchives-XXXIX-B8-277-2012.pdf

Key words: vegetation, mapping, classification, targets, multispectral

4.0 INTRODUCTION

Grass invasions represent a significant threat to biodiversity and in their aggregate may impact global aspects of ecosystem function (D'Antonio et al. 1992). This is largely due to their impact on native wildfire regimes, which typically increase in frequency and intensity where grass was previously absent (Balch et al. 2013). Early detection of new invasion fronts is critical for effective control (Hobbs et al. 1995). Remote sensing presents as an ideal mode for mapping and monitoring invasion as it affords a landscape scale view of the invasion and can be cost effective compared with laborious field work.

Remote sensing has been successfully applied to species-level discrimination where the target species covered a broad extent and possessed distinct phenological characteristics (Arzandeh et al. 2003; Wilfong et al. 2009). However, aerial photography as well as long-established multispectral satellite sensors such as Landsat (30 m GSD) and SPOT (10 m Pan GSD, 20 m XI GSD) have been described as inadequate for discriminating between grasses (Stitt et al. 2006; Gray et al. 2008). A higher degree of mapping accuracy can be achieved with airborne hyperspectral imagery but the advantages do not always justify the high cost of acquisition and interpretation (Lass et al. 2002; Gray et al. 2009). The recently launched (January 2010) WorldView-2 multispectral sensor offers a middle ground between high spatial and high spectral resolution. It provides high spatial resolution (2 m multispectral, 0.5 m panchromatic and pan-sharpened) as well as eight spectral bands (Table 11) and to date has not been trialled for detecting individual grass species.

Table 11 Spectral bands of WorldView-2 imagery

Band name	Wavelength minimum – maximum (nm)
Panchromatic	450 - 800
Coastal blue	396 - 458
Blue	442 – 515
Green	506 – 586
Yellow	584 - 632
Red	624 - 694
Red-Edge	699 - 749
NIR 1	765 - 901
NIR 2	856 - 1043

Our aim was to determine if WorldView-2 imagery could be used to discriminate invasive Buffel grass *(Cenchrus ciliaris)* in the subtropical arid parts of central Australia and whether it offers a tangible improvement on four-band (visible and near-infrared) multispectral imagery.

4.1 METHODS & MATERIALS

4.1.1 Focal Species: Buffel grass

Buffel grass *(Cenchrus ciliaris syn. Pennisetum ciliare)* is an African C4 perennial tussock grass hailed for its resistance to drought and heavy grazing in sub-tropical semi-arid rangelands throughout Australia and the Americas (Humphreys 1967; Hanselka 1988; Daehler et al. 2005; Marshall et al. 2012). However, it can rapidly invade non-target environments, increasing the frequency and intensity of wildfire, threatening biodiversity conservation as well as residential areas (D'Antonio et al. 1992; Miller et al. 2010) and efforts are now being made to prevent its spread (Daehler et al. 2005). Buffel grass has highly varied morphological and physiological characteristics. It spreads by seed and vegetatively via rhizomes and stolons. The result of this is that Buffel grass has a range of forms and can be observed growing in dense monotypic stands as well as small clumps and lone tussocks throughout the landscape. Individual tussocks can live up to 20 years, reaching heights of between 20 – 150cm and produce inflorescences ranging in colour from beige to dark purple. Older plants tend to have a less vibrantly green leaves and typically hold dead leaf at the base of the tussock (Figure 10).

There have been several published attempts to remotely detect Buffel grass in the Sonoran Desert of the USA and Mexico (Franklin et al. 2006; Puckey et al. 2007; Brenner 2011; Olsson et al. 2011; Olsson et al. 2012) and Australia (Puckey et al. 2007). Moderate resolution satellite data (MODIS and Landsat) were useful for monitoring large converted pastures over several years (Franklin et al. 2006; Brenner 2011). Franklin et al. (2006) were able to report an 8% increase in pasture coverage from 1973 to 2000. However, this approach is less useful for distinguishing invasive patches in heterogeneous mixed desert scrub (Olsson et al. 2011). In a similar scenario, Puckey et al. (2007) effectively mapped the occurrence of Buffel grass in an Australian national park from aerial survey. However, neither method is feasible for ongoing monitoring of Buffel grass infestations in natural arid Australian landscapes because localised aerial mapping is too expensive, and Landsat and MODIS do not have a high enough resolution to distinguish patchy infestations.

Figure 10 (Left) Juvenile plant growing in creek line; (Right) mature plant growing at roadside (Photographs by Victoria Marshall, northern South Australia)

4.1.2 Study area

Our study site is a 100 km^2 area located one kilometre west of Alice Springs, in central Australia (Figure 11). Selected to represent the great diversity of landscapes present in central Australia, the area includes several ridges of the MacDonnell Ranges, the townships of Larapinta, pastoral leases, dry creeks and wildlife protected areas. Dominant vegetation types include Witchetty Bush or Mulga woodlands, Ironwood Acacia woodlands and Spinifex grasslands. This arid region typically receives sporadic summer rains which can support dense infestations of Buffel grass. The grass was sown in and around Alice Springs Airport (Figure 11) in the early 1970s to prevent dust storms, and has spread out into the neighbouring regions (Cameron 2004; Miller et al. 2010). Residents have a strong understanding of its presence in the landscape. In this area there are known dense infestations along watercourses, associated alluvial soils and roadsides, sparse infestation on foot hills, becoming sparser further up hills, fire affected regions where Buffel grass is emerging first on ash beds as well as protected sites where the grass is actively controlled.

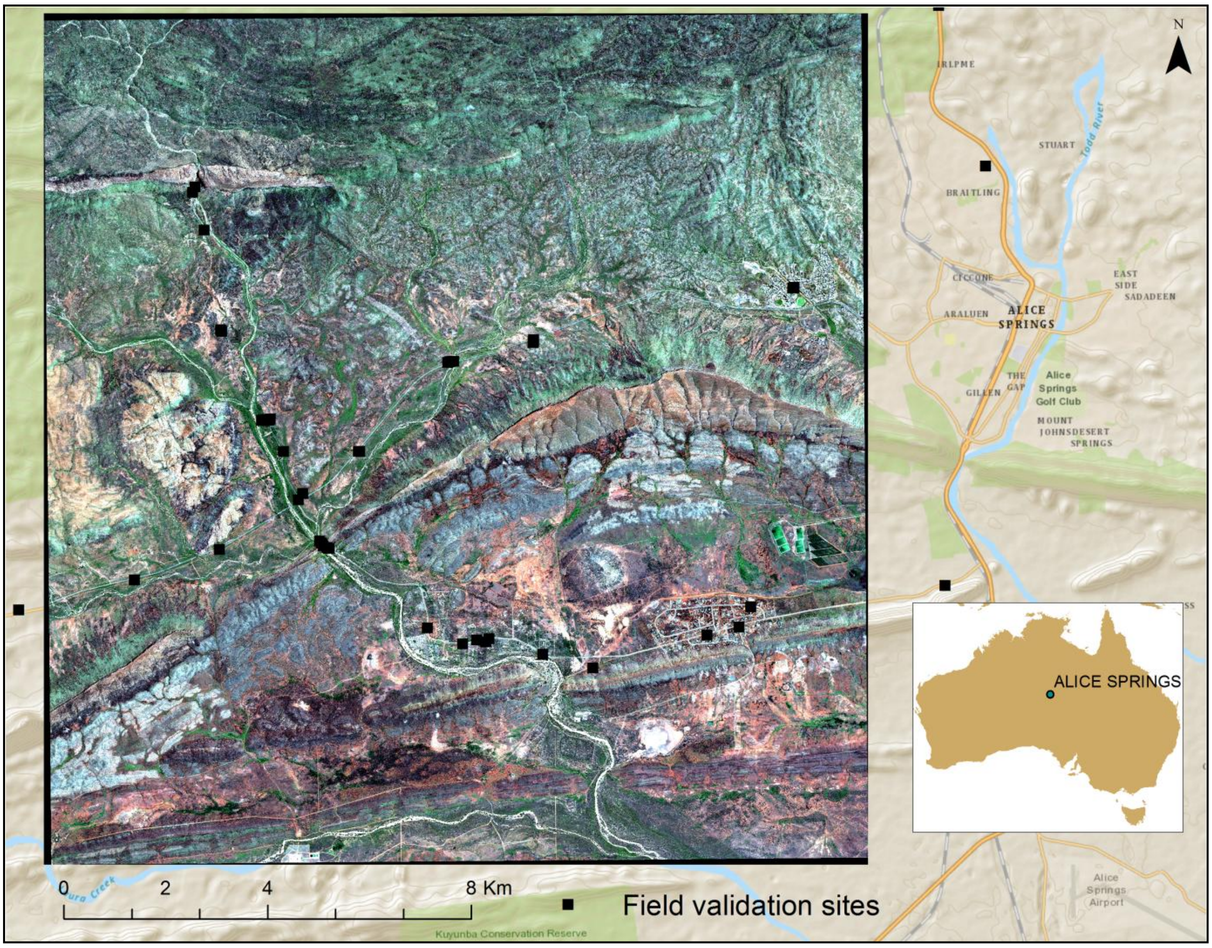

Figure 11 Study site 1km west of Alice Springs in central Australia. WorldView-2 imagery displayed in true colour covering the total extent of the study site. Ground validation sites are marked (black squares).

4.1.3 Imagery

The 10 × 10 km WorldView-2 image was acquired on 22 January 2011, following approximately 80 mm of rain over the preceding month. The region had also received record high volumes of rain between August and November 2010 due to tropical cyclones and floods in Northern Australia. Thus, high densities of all ephemeral plants were expected. Cloud-free WorldView-2 imagery was captured at 1330 hours at an off-nadir angle of 13 degrees. We corrected for atmospheric effects using Fast- Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) in ENVI 4.8. A Mid-Latitude Summer Atmospheric Model, Rural Aerosol Model and an Initial Visibility of 40 km were applied. All our analyses are based on the multispectral image, and in this instance we do not utilise the pan-sharpened image provided.

4.1.4 Analysis

Vegetation discrimination

Reference spectra for Buffel grass and surrounding dominant vegetation types were extracted from the imagery. Reference spectra were selected by careful interpretation of the imagery that was aided by local knowledge, vegetation maps, and image analysis tools including vegetation indices and variance analyses.

Initially we applied a vegetation index and assigned a threshold to isolate vegetation components of the imagery. In this case, we applied the traditional Normalised Difference Vegetation Index (NDVI) using the Red and NIR-2 bands. The NIR-1 band could also be used. We adopted this traditional approach because of the high levels of photosynthetically active vegetation present in the region. Based on NDVI values, a generous mask (NDVI > 0.3) was applied.

To further aid image interpretation, we explore the key factors contributing to variation in the image using a principal component analysis (PCA). This analysis linearly transforms correlated bands into uncorrelated components that represent variation in the data, reducing redundancy in the data, while retaining all eight bands.

Ultimately, we chose to collect reference spectra for Buffel grass in various conditions, which we named “Lush” (healthy actively growing plan), “Grazed” (Buffel grass pasture being grazed) and “Burnt” (Buffel grass burnt or emerging on burnt seedbed). Reference spectra were also collected for broadly categorised surrounding vegetation including, “Mulga (Acacia woodlands*)*, “Tree” (mostly Eucalyptus observed in creek lines) and *‘*Natives” (native grasses). Between 5 and 10 spectra were collected for each vegetation cover type and their averages were used for image classification.

Spectral separability

The spectral separability of cover-type spectra was examined using a linear discriminant analysis (LDA). LDA is a method used to discriminate between groups of samples based on a linear transformation of predictor variables, which in this case are the eight image bands (Rencher 2002). LDA was cross validated using the leave-one-out technique (Rencher 2002). To examine the importance of the additional bands on the classification, the LDA was performed for 4 bands (blue, green, red and NIR1) as well as the full 8 bands. Outlying samples were excluded and spectral groups were averaged prior image classification.

Classification

For target detection, we utilised Mixture Tuned Matched Filtering (MTMF) classification method normally applied to hyperspectral imagery (Williams et al. 2002). Lush Buffel grass was used as the target spectrum. Background spectra were specified as Native, Mulga and Tree and included Grazed and Burnt Buffel grass. A preliminary Minimum Noise Fraction Transformation was applied to the imagery. The MTMF produced two grey scale images: Matched Filtering Score (MFS) and Infeasibility Score (IS). Areas similar to Buffel grass reference spectra return high MFS and a low infeasibility score; the Matched Filtering score was divided by the Infeasibility to produce a grey scale image of spectral similarity to Buffel grass, where higher values are the most like Buffel grass. A MFS/ IS threshold of >0.06 was used to classify Buffel grass in the imagery.

Accuracy Assessment

To validate the classified image, ground data were collected on 20-22 March 2011, two months after image capture. The presence or absence of Buffel grass at low (1-34%), medium (35-84%), and high (85-100%) covers was recorded at points accessible by roads throughout the study area. Each record represented a circular area with a diameter of approximately 10 metres. This diameter was selected to account for the spatial accuracy of the WorldView-2 product (10.16 metres) as well as of the Garmin GPS receiver (2 m). Approximately 40 records were collected (Figure 11). From the 40 field observations an error matrix was used to calculate the accuracy of the classification.

4.2 RESULTS

4.2.1 Vegetation discrimination

The NDVI threshold (>0.3) classified greater than 50% of the imagery as green vegetation (Figure 12). Northern facing slopes, alluvial environments and converted pastures contain the most photosynthetic vegetation. Buffel grass is not distinguishable from other vegetation types.

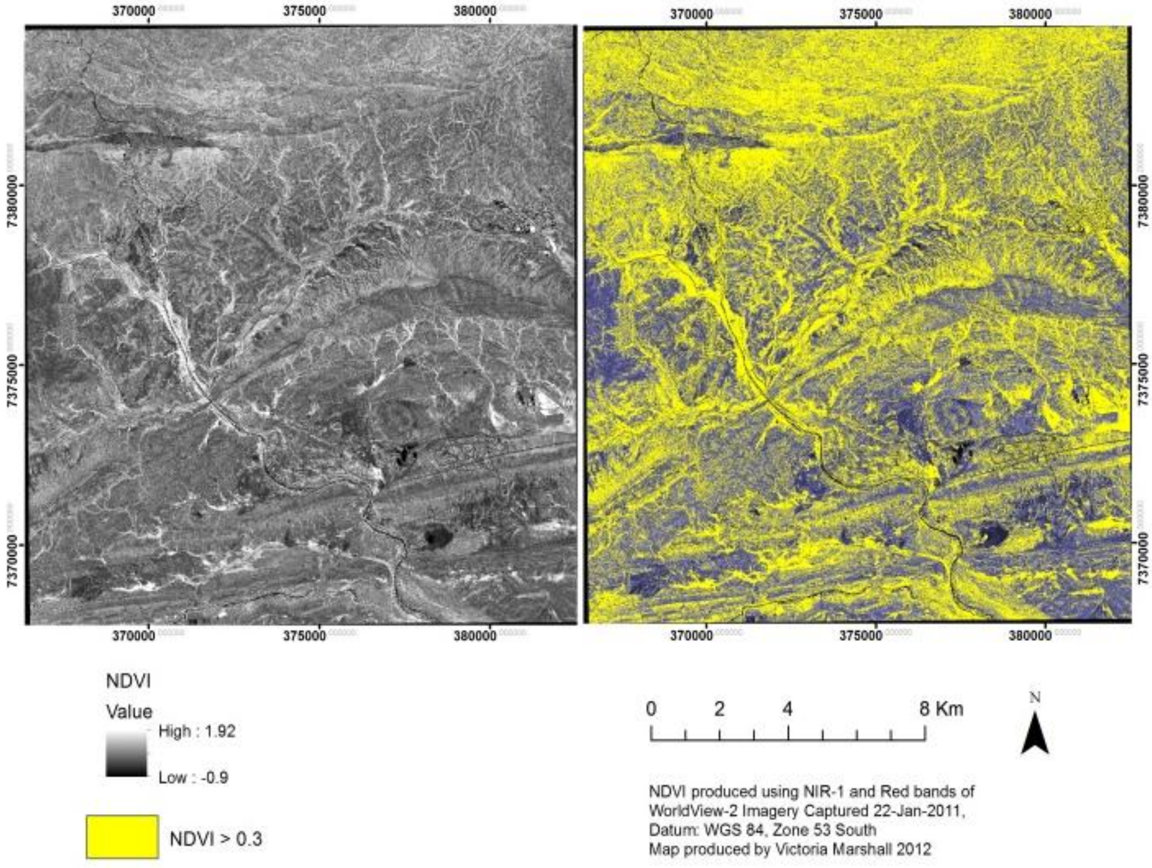

Figure 12 NDVI of WorldView-2 imagery utilising the NIR-2 and Red bands (Left); NDVI values >0.3 (yellow) representative of photosynthetic vegetation in the landscape (Right)

The result of the principal component analysis was 8 principal components, where the first three components represent approximately 95% of the variation in the image (Figure 13). Based on eigenvectors we can see that principal component (PC) one, represents overall albedo, PC-2 captures green vegetation and PC-3 captures areas where there is a strong contrast between Red and the other wavebands. For example, PC-2 shows low eigenvector values in band 5 (red) and high in the NIR (bands 7 and 8), thus land cover components with a strong difference between red and near-infrared, such as actively growing vegetation are highlighted in this image. PC-2 was most useful in helping to select reference spectra, and on visual inspection of the whole image scene appears to show a tighter classification of photosynthetic vegetation than the NDVI. Specifically, vegetation along drainage lines was well defined.

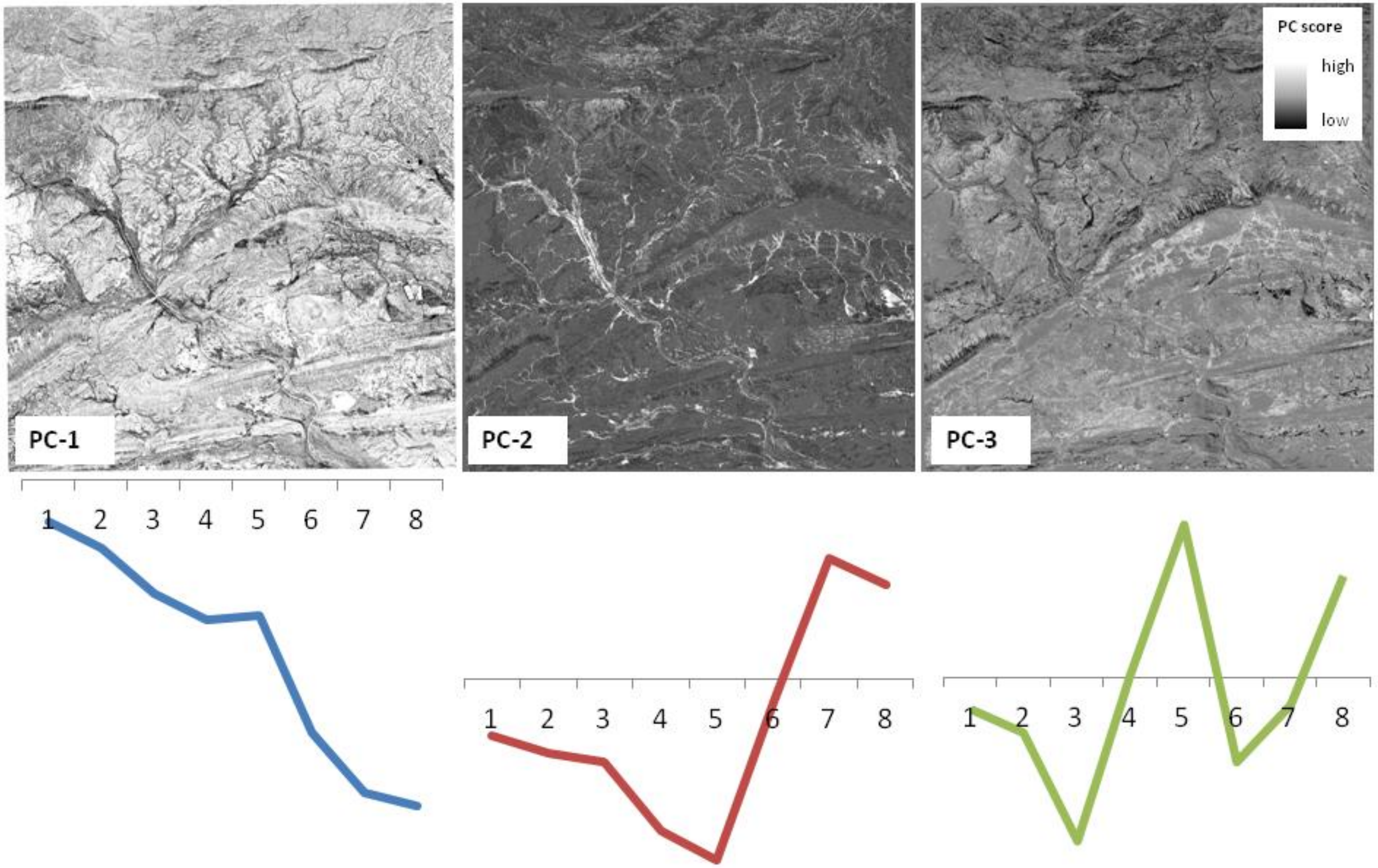

Figure 13 The first three principal components for the WorldView-2 image. Eigenvector values for each PC are presented below the associated image.

Representative spectra are presented in Figure 14. The figure shows that Lush Buffel grass and Tree have a stronger response in the NIR region than any other cover type, followed by Burnt Buffel grass and Mulga. Natives have low spectral responses in the NIR and also demonstrate little variation in the visible region. Variation exists within the spectra of the different cover types. Trees and Natives have the least spectral variation, while the Buffel grass and Mulga classes have internal variation that is particularly strong in the NIR regions.

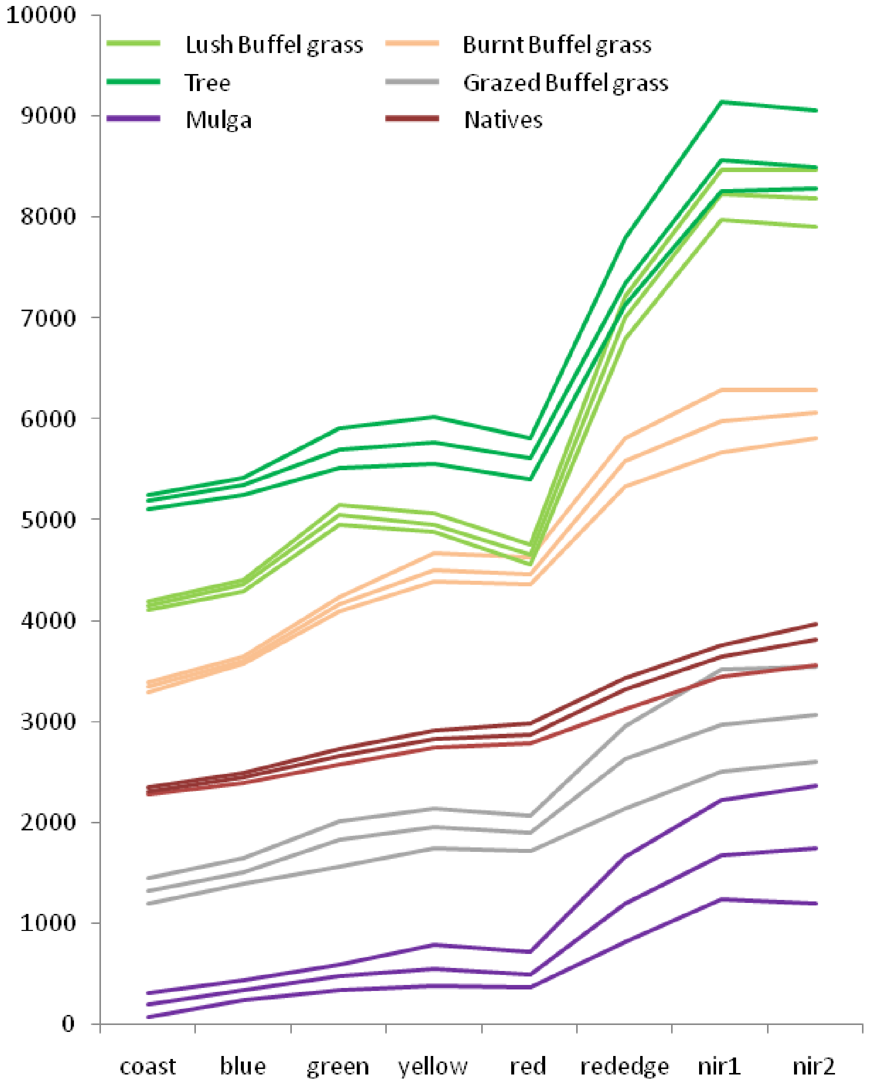

Figure 14 Five to ten spectral signatures were collected from the WorldView-2 scene for each cover class (Lush Buffel grass, Tree, Mulga, Burnt Buffel grass, Grazed Buffel grass and Natives); the minimum, mean and maximum spectra for each cover class are graphed. For display purposes, each spectral group is off-set by increments of a thousand.

4.2.2 Spectral separability

The spectra for each vegetation cover class showed high separability based on LDA for both four and 8 band analysis. Predictions based on LDA (Table 12) are marginally stronger (2%) using four bands compared with 8 bands. Predictions based on either four or 8 bands indicate that the Native class may be misclassified at a rate of 30% as Grazed Buffel grass or Mulga. For predictions based on eight bands there is an additional error; Burnt Buffel grass may be misclassified at a rate of 20% as Grazed Buffel grass. Linear discriminators LD1, LD2, and LD3 combined represent greater than 80% of the trace in both analyses.

Table 12 Class predictions from the linear discriminant analysis using four (red, blue, green, NIR1) and 8 bands of the WorldView-2 imagery to discriminate between Buffel grass from various other vegetation types. Correct classifications are presented in green, misclassifications are presented in red.

	Burnt	Grazed	Lush	Mulga	Natives	Tree
Prediction based on four-bands (blue, green, red, NIR1)						
Burnt Buffel grass	**5**					
Grazed Buffel grass		**3**			*2*	
Lush Buffel grass			**6**			
Mulga				**6**	*1*	
Natives					**7**	
Tree						**6**
Prediction based on eight-bands						
Burnt Buffel grass	**4**	*1*				
Grazed Buffel grass		**3**			*2*	
Lush Buffel grass			**6**			
Mulga				**6**	*1*	
Natives					**7**	
Tree						**6**

By examining the contribution of each spectral band to the LDs we can see that in this instance the visible part of the spectrum is the most important for discriminating between vegetation types (Table 13). Blue and Green bands are particularly significant, with Infrared contributing least to the discrimination.

Table 13 Contribution of each spectral band to linear discriminators (LD) 1, 2 and 3 for LD analysis using four (red, blue, green, NIR1) and 8 bands of the WorldView-2 imagery to discriminate between Buffel grass from various other vegetation types. Contributions typed in bold are the two largest contributors for each LD.

	LD1	LD2	LD3
four-bands (blue, green, red, NIR1)			
Blue	**-0.00803**	**-0.01977**	0.013034
Green	**0.009886**	0.005243	**-0.02967**
Red	0.005438	**0.011704**	**0.013119**
NIR1	-0.00564	0.000486	0.004503
*Proportion of Trace	0.627	0.248	0.1189
eight-Bands			
Coast	-0.00079	**0.02255**	-0.00981
Blue	**-0.01732**	0.01051	-0.00065
Green	**0.021294**	**-0.02125**	**0.029956**
Yellow	0.003094	-0.00596	-0.00037
Red	0.006336	-0.00443	**-0.01628**
Red Edge	-0.00952	0.008127	-0.00191
NIR1	-0.00633	0.000283	-0.00838
NIR2	0.005092	-0.00336	0.004997
*Proportion of Trace	0.5579	0.3043	0.1188

4.2.3 Image classification

Image classification based on MTMF threshold (> 0.06) identifies less than 10% of the image scene as Buffel grass (Figure 15). The classification indicates that Lush Buffel grass tends to occur on rich alluvial soils surrounding creek lines and drainage depressions. Spectral matching was strongest surrounding the major creek line which runs north-south through the image. Figure 16, enlargement A shows that where this major creek line passes through a gap in the ridge. Here the classification has effectively discriminated between Buffel grass and other highly photosynthetically active understorey from trees present in the dry creek. However, we observed Buffel grass growing up the hill slope mixed with other grasses, and this low density Buffel grass is not classified. Figure 16, enlargement B highlights that the classification does not distinguish Buffel grass from other highly photosynthetically active vegetation; the example depicts the township sports oval, which is not sown with Buffel grass.

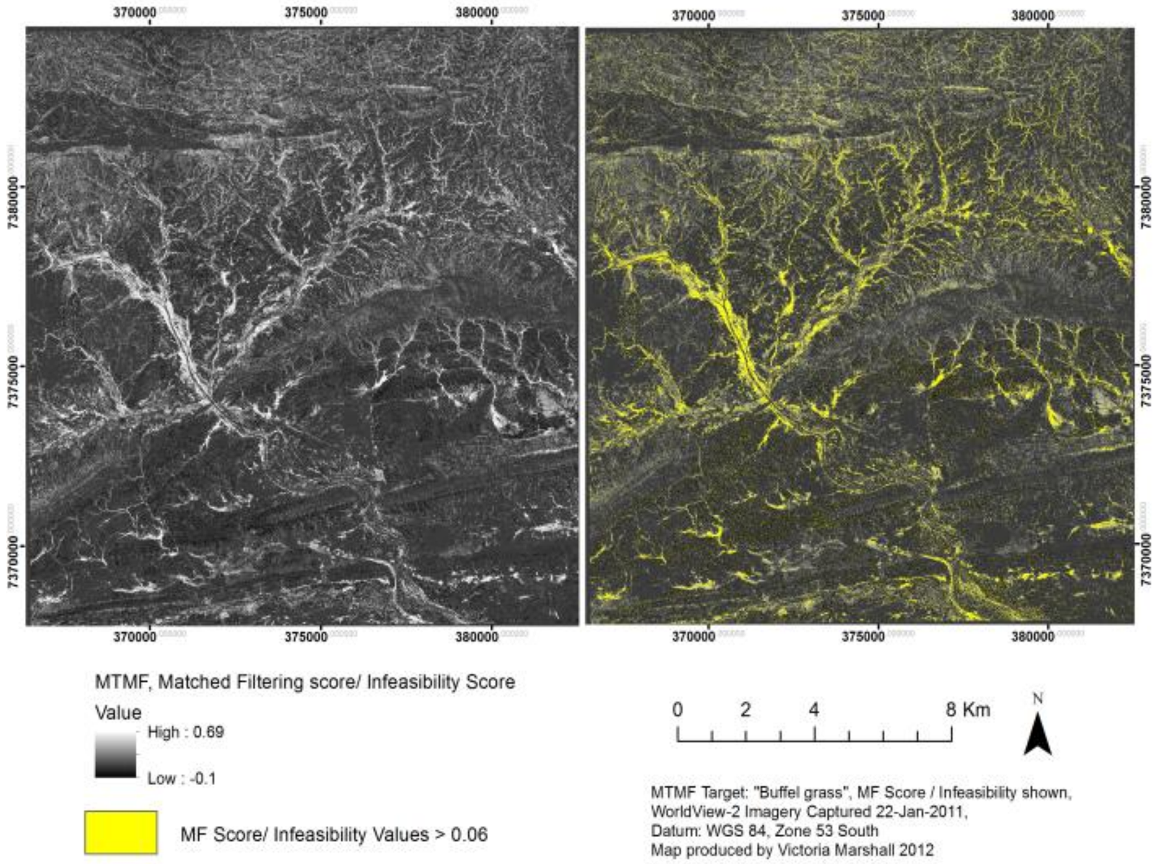

Figure 15 Matched filtering score/ Infeasibility score representing similarity to Buffel grass reference spectra. Values >0.06 (yellow) represent the best classification of Buffel grass (Right)

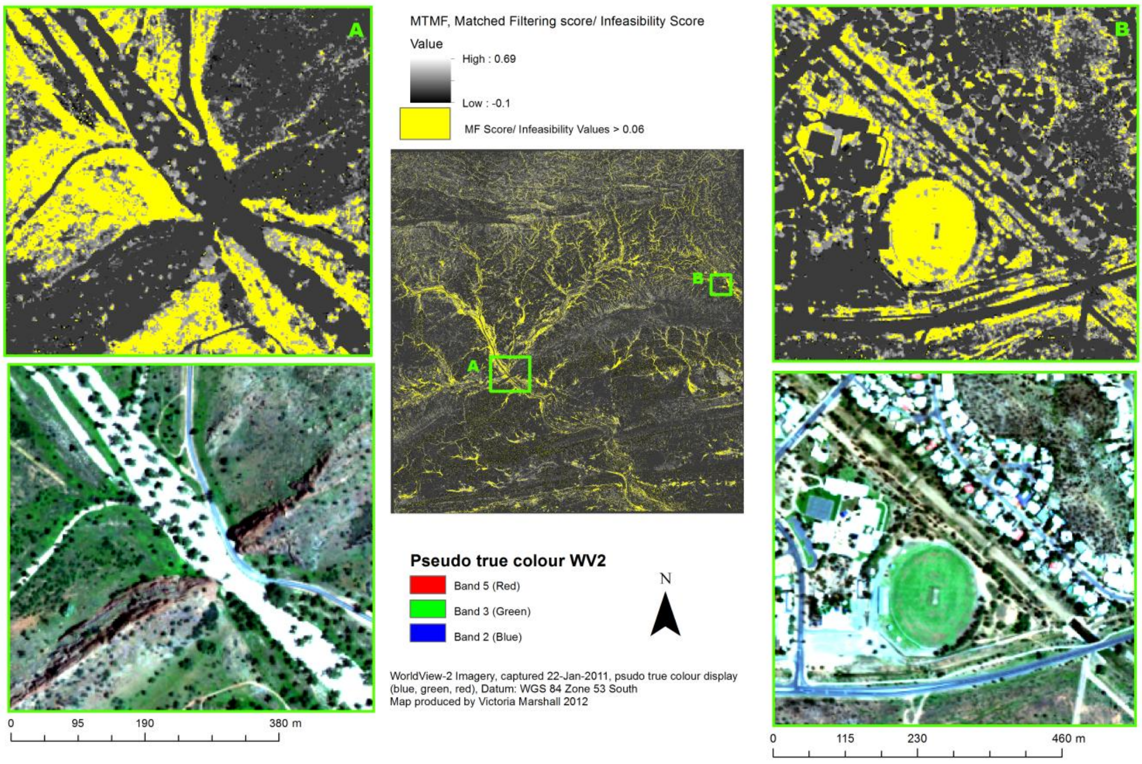

Figure 16 MTMF-based classification of Buffel grass (Yellow) on WorldView-2 imagery (Centre image). Enlargements A and B highlight regions of under and over classification of Buffel grass. The enlargements are also shown in Pseudo-true colour to aid interpretation.

The overall accuracy of the classification was 59% (Table 14). Absence of Buffel grass is mapped with 50% accuracy, and error is mostly attributed to Commission. Presence of Buffel grass is mapped with 44.1% accuracy, omission error 44.1% while the commission error is 11.7%

Table 14 Accuracy assessment of Buffel grass mapping comparing on ground data to WorldView-2 image classification of Buffel grass presence and absence

		Imagery			Omissions	Commissions	Mapping Accuracy
		Absent	Present	Total Possible			
Ground	Absent	6	2	8	25.0 %	50 %	50%
	Present	15	19	34	44.1 %	11.7 %	44.1 %
	Total	21	21	42			
	Overall Accuracy = (6 + 16)/ 42 *100 = 59.5%						

4.3 DISCUSSION

Monitoring grass invasion is crucial for effective control. Remote sensing presents as a cost effective means to do this. However, for species which are spectrally similar to their surroundings remote detection can be challenging. We have presented a method for detecting lush (highly photosynthetic) Buffel grass in a diverse central Australian environment using eight-band multispectral imagery, WorldView-2. We use Mixed Mixture Tuned Matched Filtering to classify Buffel grass. The classification indicated that Buffel grass is prevalent in riparian environments, on alluvial plains, and has a strong presence on the granitic-mulga woodlands in the northern half of the study area. Buffel grass was classified in the imagery with 59% overall accuracy.

There are several likely sources of error in the overall accuracy assessment. The first relates to the two month time lag between image capture and field data collection, during which there was considerable rainfall and highly active growth of all ephemeral plants. Secondly, Buffel grass can be observed growing beneath trees, particularly Mulga trees, in the field. This may result in under classification of Buffel grass on the imagery. Finally, in terms of mapping Buffel grass abundance, the image classification may be more accurate than the assessment suggests, because low density infestations were under-classified. The accuracy assessment may return stronger results if it was based on density rather than presence-absence (Elghazali et al. 2001). A greater number of ground validation sites (here $n = 40$) would be required to test this.

Contrary to expectations, linear discriminant analysis of spectra using eight bands and four bands (blue, green, red and NIR1) of the WorldView-2 imagery does not indicate a benefit in using the additional four bands for this application. This is probably due, in part, to a high level of variation within the spectral groups, which is particularly observable in the NIR2 and yellow bands (Figure 14). In this image, the landscape was dominated by high volumes of photosynthetically active, green vegetation, and thus green and blue bands present as the most effective discriminators. We consider that had the image been captured during a dry season, the yellow and NIR bands may have been a significant contributor to the effective discrimination of Buffel grass from surrounding vegetation. Hence, eight bands may improve spectral separability of Buffel grass under different seasonal conditions.

In conclusion, high resolution (2 m GSD) multispectral satellite imagery has potential for mapping high density Buffel grass infestations in varied arid landscapes, and may be useful for monitoring purposes. The enhanced eight-band spectral resolution, when all ephemerals display vigorous growth, was of less importance; typical four-band imagery comprising the suite of blue, green, red and near-infrared bands was adequate for Buffel grass mapping. Visible bands (blue and green), were the most important discriminators. Future research is required to determine if there is an added benefit to using eight spectral bands under different seasonal conditions.

Chapter Five

Detecting new Buffel grass infestations in Australian arid lands: evaluation of methods using high-resolution multispectral imagery and aerial photography

Marshall, V.M, Lewis, M., Ostendorf, B. (2013) "Detecting new Buffel grass infestations in Australian arid lands: evaluation of methods using high-resolution multispectral imagery and aerial photography" Environmental Monitoring and Assessment (Accepted: 30 September 2013, *In press*)

Key words: remote sensing, aerial photography, high resolution, invasive species, natural resource management, *Cenchrus ciliaris, Pennisetum ciliare*

Abstract. We assess the feasibility of using airborne imagery for Buffel grass detection in Australian arid lands and evaluate four commonly used image classification techniques (visual estimate, manual digitisation, unsupervised classification and Normalised Difference Vegetation Index (NDVI) thresholding) for their suitability to this purpose. Colour digital aerial photography captured at approximately 5 cm of ground sample distance (GSD) and four-band (visible- near-infrared) multispectral imagery (25 cm GSD) were acquired (14 February 2012) across overlapping subsets of our study site. In the field, Buffel grass projected cover estimates were collected for quadrates (10 m diameter), which were subsequently used to evaluate the four image classification techniques. Buffel grass was found to be wide spread throughout our study site; it was particularly prevalent in riparian land systems and alluvial plains. On hill slopes Buffel grass was often present in depressions, valleys and crevices of rock outcrops, but the spread appeared to be dependent on soil type and vegetation communities. Visual cover estimates performed best (r^2 0.39), and pixel-based classifiers (unsupervised classification and NDVI thresholding) performed worst (r^2 0.21). Manual digitising consistently underrepresented Buffel grass cover compared with field and image-based visual cover estimates; we did not find the labours of digitising rewarding. Our recommendation for regional documentation of new infestation of Buffel grass is to acquire ultra-high resolution aerial photography and have a trained observer score cover against visual standards and use the scored sites to interpolate density across the region.

5.0 INTRODUCTION

Encroachment of invasive Buffel grass (*Cenchrus ciliaris* L. *Pennisetum ciliare*) into arid and semi-arid ecosystems requires early detection if we are to have any hope of controlling its spread. Originally from Africa, this drought-hardy bunch grass was introduced into Australia and the Americas as rangeland pasture where it remains an important resource (Smyth et al. 2009; Brenner 2011). Outside intended areas, it is a concern for natural resource managers because it accumulates dead matter, promoting fire in fire-intolerant systems, homogenising landscapes and threatening environmental and cultural values of infested areas (D'Antonio et al. 1992; Miller et al. 2010).

Comprehensive species distribution maps are invaluable to the containment of all invasive species (Stohlgren et al. 2006). Field-based mapping is only feasible over localised areas and is typically restricted by road access, to sites of particular significance, or to sites identified for strategic control (where an isolated occurrence is observed). These areas are mapped as a prelude to control within this area, and there is usually some prior knowledge of the distribution before localised mapping efforts are undertaken. In the remote desert landscapes of Australia, where Buffel grass thrives and is widespread, field-based mapping is inadequate; the alternative is a remote sensing approach.

Remote sensing has been proven as an effective tool for community level vegetation mapping and monitoring (Ramakrishna et al. 1996; Mehner 2004; Brink et al. 2009). Discrimination of individual plant species is more difficult due to the complexity of species intermixing with surrounding vegetation and spectral variability within individual species. Remote sensing approaches to species-level plant mapping have been most successful when the target species possess distinctive spectra, has a large structure or grows in large stands relative to the spatial resolution of the imagery, shows vigorous population growth; and when the phenological stages of growth are taken into account during spectral signature collection (Ustin et al. 2002; Ge et al. 2006; Andrew et al. 2008; Hestir et al. 2008; Wang et al. 2008; Blumenthal et al. 2009; Jia et al. 2011; Padalia et al. 2013). This presents several challenges for the remote detection of Buffel grass because most grasses are spectrally similar, the size of stands is variable and with unknown limits, vigorous growth is a response to rainfall and is not strictly seasonal, and there is a degree of intra-species variation.

Nonetheless, in the Sonoran Desert of Mexico and the USA several studies demonstrate success in remote detection of Buffel grass (Franklin et al. 2006; Olsson et al. 2011; Brenner et al. 2012). These studies primarily utilised moderate resolution satellite imagery, useful for monitoring large established infestations or pastures. Olsson et al. (2011) was able to distinguish Buffel grass in heterogeneous mixed desert scrub with the greatest success by integrating hyperspectral measurements of plant spectra collected in the field. However, these approaches are not necessarily useful for detecting new infestations as an alternative to field work.

For remote detection of emerging infestations, individual tussocks, less than 0.5 m in diameter, must be definable. This requires a high spatial resolution with a ground sample distance (GSD) that is below 25 cm, i.e. half the smallest unit to be classified (Myint et al. 2011). An advantage to using aerial imagery is that acquisition timing is extremely flexible. This is critical, when working with grasses that rapidly green up in response to rainfall, and almost as quickly dry off or burn to ash, leaving a very small window of time when imagery can be captured.

There are many challenges associated with using aerial imagery such as the limited spatial coverage (footprint) of image scenes, the quality of images being strongly weather dependant, and the spatial coverage needing to be tailored to a specific project (Gergel et al. 2010). Further challenges include data management, processing time and cost. These factors, combined with uncertainty regarding the accuracy of classifications, means aerial imagery is underutilised by natural resource managers.

Approaches to aerial image classification vary in regard to accuracy, consistency, time consumption and required producer expertise. Visual interpretation can be highly accurate; it requires minimal image preparation, and uses human knowledge to make logical decisions (Gergel et al. 2010). This method can be documented either by digitising infestations (Olsson et al. 2012) or by using visual standards to categorically record species cover at selected locations across the study site (Puckey et al. 2007). Digitising is extremely laborious but less subjective than visual cover standards (Gergel et al. 2010).

Pixel-based classifications are semi-automated, systematic, and repeatable and require less interpretation time. However, these rely solely on spectral separation of the target species from surrounding land cover, which is complex in the case of this variable grass. In some ways, it is also less suited to analyses at high spatial resolutions because of the spectral diversity within the tussocks. For example, the sunlit side of tussocks may present a different spectral category to the shadowed side, or dry foliage a different category from green foliage, resulting in a speckled “salt and pepper” effect (Myint et al. 2011). More recently, object-based classifiers have been developed, which, like pixel-based classifiers, are systematic, consistent and repeatable, but they better mimic human perception of objects (Laliberte et al. 2004; Walter 2004; Yu et al. 2006; Meneguzzo et al. 2012). Object-based classification algorithms are not yet well developed and require expert production.

Our goal is to explore the potential of aerial imagery for detection of Buffel grass populations in Australian desert country. Specifically, we examine 5-6 cm (GSD) ultra-high resolution colour digital aerial photography and 25 cm (GSD), four-band (visible-near-infrared) multispectral imagery. We compare four different, yet common classification approaches; visual cues, manual digitisation, unsupervised classification and Normalised Difference Vegetation Index (NDVI) thresholds and assess each for their suitability to Buffel grass discrimination. The research was conducted with the long-term aim of developing a method for early detection of Buffel grass in remote arid landscapes that could be used by natural resource managers.

5.1 METHODS & MATERIALS

5.1.1 Focal Species: Buffel grass *(C. ciliaris L. P. ciliare)*

Buffel grass is a perennial, summer growing (C4) African bunch grass (Sharif-Zadeh et al. 2001). It reproduces via seed and rhizomes and as a result can be seen in the landscape as both lone tussocks and dense monocultures. It does not drop its leaves; they accumulate at the base of the plant, often forming a ring of dry foliage around the tussock. The grass is spread by wind, water and traffic. In arid environments of Australia, where this study is based, it is typically found at highest density in riparian environments, depressions, and wherever soils are disturbed, including roadsides, construction sites and fire beds (Marshall et al. 2012). The plant responds rapidly to rain, and often emerges before native grasses. It is also quick to dry-off and burn. The window for image capture of growing plants is brief; in Australia we consider it is usually restricted to about a month after the first summer rains.

5.1.2 Study area

Located in the remote far north-west corner of South Australia, the study site occupies 15 x 12 km of the aboriginal owned A<u>n</u>angu Pitjantjatjara Yankunytjatjara (APY) lands. The site encompasses two indigenous communities Kalka (26° 7'11.50"S, 129° 8'59.04"E) and Pipalyatjara (26° 9'37.45"S, 129°10'20.64"E) (Figure 1), with a combined population of less than 350. Climate is arid, with hot summers, mild winters and annual rainfall below 300 mm. Elevation ranges from 650 m to 900 m. Plains comprise alluvial and fluvial sediments, vegetated by *Aristida* grasslands, sparsely distributed low shrubs and *Hakea* trees. These grasslands are increasingly dominated by Buffel grass. The Tomkinson ranges (Figure 17) comprise mafic rock dominated by Spinifex hummock grasses; ranges in the north-west of the study site (Figure 17) comprise felsic rock dominated by *Enneapogon* sp. grasses.

Buffel grass was introduced by direct seeding around Kalka in October 1987, along with *Cenchrus setigerus* and native drought tolerant shrubs, *Atriplex nummularia*, *Acacia kempeana* and *Acacia ligulata* to combat dust storms on the alluvial flats; dust became a problem after an uncontrolled wildfire burnt a substantial area near the settlements, drought followed, and vegetation never regenerated. As a result of the direct seeding in 1987, this region is now largely dominated by Buffel grass.

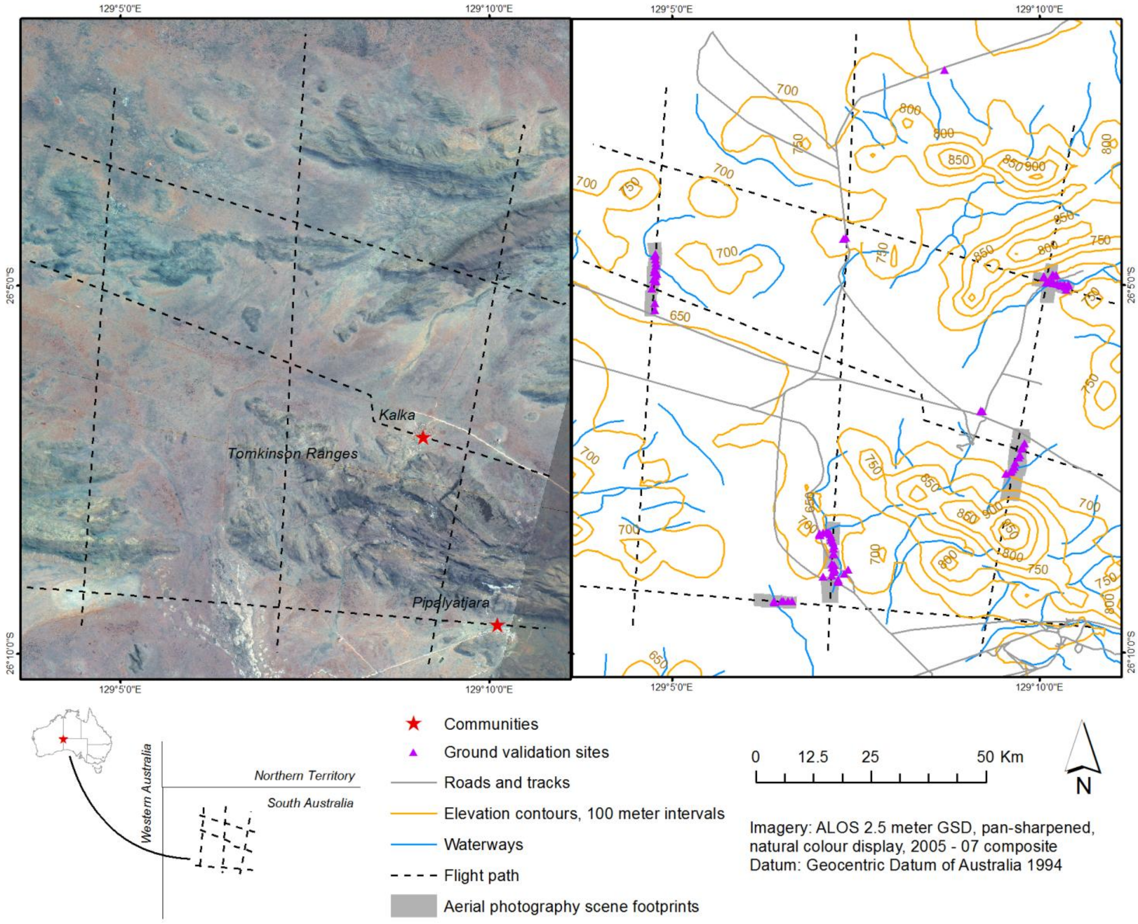

Figure 17 Study site and flight path design. Left: flight paths. Right: field sample sites, terrain contours in which the light aircraft was navigating, and the image scenes of high quality which overlapped our field sites. These maps were prepared in the Geocentric Datum of Australia 1994.

5.1.3 Imagery

Colour digital photography, and four-band (visible to near-infrared (NIR)) multispectral images were obtained over the study area. Image specifications are given in Table 15. The imagery was acquired on 14 February 2012 between 1134 and 1430 hours. Multispectral imagery was flown after the aerial photography from 1352 hours in the afternoon; consequently, shadow effects vary between the images. Conditions at the time of image capture were slightly hazy with less than 1% high cirrus cloud cover. Buffel grass was approximately 50% dried off on the day of image capture.

Table 15 Image specifications for aerial imagery captured February 2012 over the Kalka-Pip Homelands, Australia

Imagery	Sensor	Flying Altitude	Footprint	Ground Sample Distance (GSD) or pixel size	Spectral resolution
Digital aerial photo	Nikon D3X digital camera	305 m	~ 240 x 360 m / frame	5-6 cm	Visible; 3 band
Airborne Multispectral	Spec Terra digital multispectral sensor	1067 m	Variable	25 cm	Visible-NIR, 4 bands: 450nm ± 10nm FWHM (Blue) 550nm ± 10nm FWHM (Green) 675nm ± 10nm FWHM (Red) 780nm ± 10nm FWHM (Near-infrared)

The aerial photography was acquired for a grid of 3 × 3 transects across the study site (north-south transects approx. 17 km; east-west transects approx. 12 km; spaced 5 km apart) (Figure 17). Transects were positioned to capture the diversity of vegetation and geological settings, while avoiding high elevations that are potentially dangerous for aerial navigation (Figure 17). Photography was received as 930 un-georeferenced frames, in TIFF format. To save time georeferencing these frames individually, three- five frames were stitched together in the automated image matching program, Microsoft Image Composite Editor (ICE). Image frames were exported from ICE as JPEG files, georeferenced in ArcGIS, and saved as raster data using the minimum cell size for the image. These raster files were used for all subsequent analyses.

The four-band imagery, collected using the Spec Terra multispectral sensor, was acquired for three smaller areas, in highly diverse local environments, and overlapping the aerial photography flight paths (Figure 18). The multispectral data were delivered corrected for radiometric and geometric artefacts, as orthorectified and georegistered mosaics in TIFF format. All image analysis was carried out in the 1994 Geocentric Datum of Australia, projected to UTM zone 52.

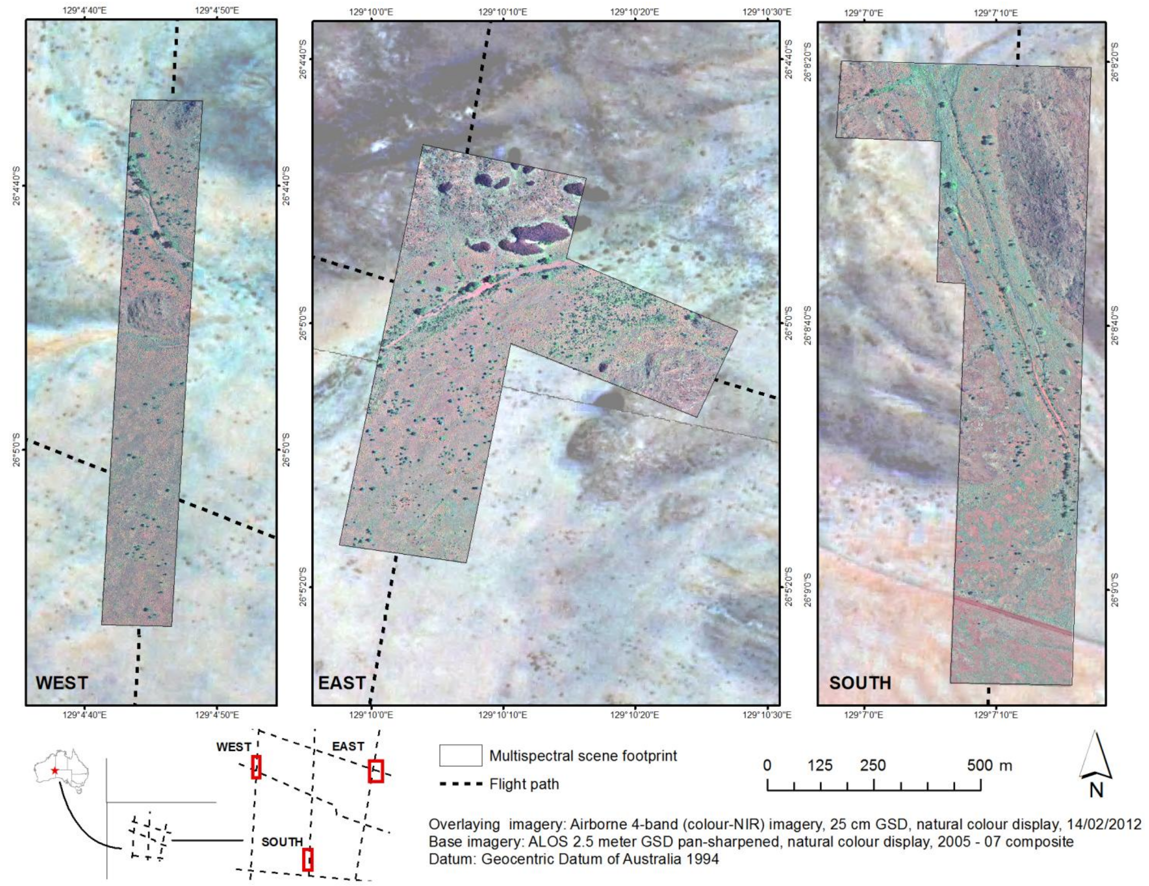

Figure 18 Coverage of Four-band Spec Terra imagery for aerial survey of Buffel grass in the Kalka – Pipalyatjara homelands of central Australia. Three Spec Terra panels were acquired in the west, east and south of the study area. These panels were designed to overlap the flight path for aerial photography collection and represent the varied landscape. The Spec Terra data are presented with a natural-colour display. The underlying image on all three maps is ALOS 2.5 m GSD pan-sharpened imagery, 2005-2007 composite, natural colour display. These maps are prepared in the Geocentric Datum of Australia 1994.

5.1.4 Ground Validation Sites

Field work was conducted from 7 to 12 February 2012. Selection of sites for ground validation was governed by *in-situ* interpretation of environmental units, such as vegetation structure, soil colour and land use, aided by a 2007 ALOS colour mosaic of the region (2.5 m GSD). The goal was to represent the diversity of landscapes in which Buffel grass was present or absent and at varying densities. In total, 95 field sites were documented. Within these circular sites (10 m in diameter) projected cover (the vertical projection of plant foliage onto a horizontal surface) was estimated for Buffel grass and land-cover units categorized as "herbs and forbs", "other grasses", "woody", "leaf litter" and "soil". Cover for each cover type was recorded as discrete classes: absent, 0%; low, 0-25%; moderate-low, 25-55%; moderate-high, 55-85%; and high, 85-100% (Figure 19).

The centre point of each ground validation site was recorded using a Garmin eTrex High Sensitivity hand-held global positioning system receiver, which achieved a spatial accuracy of approximately 2-5 m.

For remote sensing analysis, the ground validation sites were co-registered to the aerial photography and separately to the multispectral imagery using the GPS coordinates recorded in the field, and personal knowledge on the site. Of the 95 sites 18 lay outside of the imagery coverage. A further 41 were not used because of image quality (which diminished over hilly terrain), obstruction from trees, or insufficient geographical information to accurately place the site. Of the remaining sites, 43 lay within the coverage of the multispectral image scenes. Ultimately, a total of 53 and 43 sites were used for interpretation and classification of the aerial colour photography and four-band multispectral imagery, respectively.

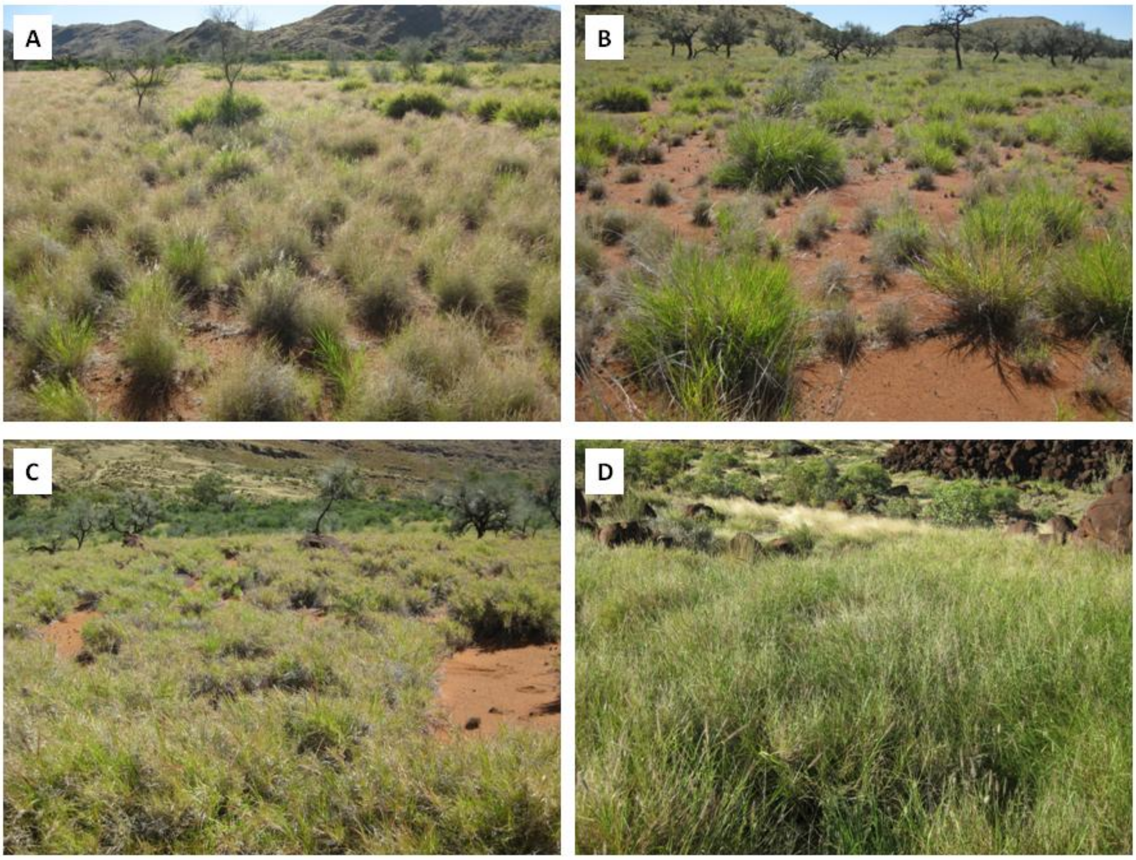

Figure 19 Buffel grass as observed in the field at low 0-25% (A), low –moderate 25-55% (B), moderate – high 55-85% (C) and high >85% (D) projected cover. The dominant grasses in panel A are *Aristida* sp.

5.1.5 Aerial photography image classification

We evaluated three commonly used image classification techniques for discriminating and quantifying Buffel grass in the aerial photography including visual cover estimates, manual digitisation, and a pixel-based unsupervised classification. Classifications were run separately for each field site (53 sites × 3 approaches).

Visual cover estimates for each ground validation site were scored using the same cover classes employed in the field survey. For consistency sites were viewed at a scale of 1:125 to make the estimates. Visual standards (Figure 20)) also aided in making observations consistent.

For the manual digitisation method, individual Buffel grass plants or clumps within the 10 m diameter circular plots were digitised from the imagery, at a display scale of 1:125 m. The digitiser did not alter the viewing scale in order to more precisely circle plants. The total digitised area of Buffel grass for each site was then tabulated.

For the pixel-based assessment, an unsupervised classification was performed on the imagery at each site. A circular area of a diameter of 30 m, centred on the ground validation site, was used to run the classification. This accounted for the possibility to have a “Buffel grass” class even if Buffel grass was not present within the more tightly-prescribed sample site. The classification was performed using the Iso Cluster Unsupervised Classification tool in ArcGIS 10 Spatial Analyst. The number of classes was set to 20; classes most representative of Buffel grass were then manually aggregated on the basis of visual examination. The aggregation process is producer-directed, allowing for some flexibility in the number of classes selected as representative of Buffel grass. The total area classified as Buffel grass for each site was then tabulated.

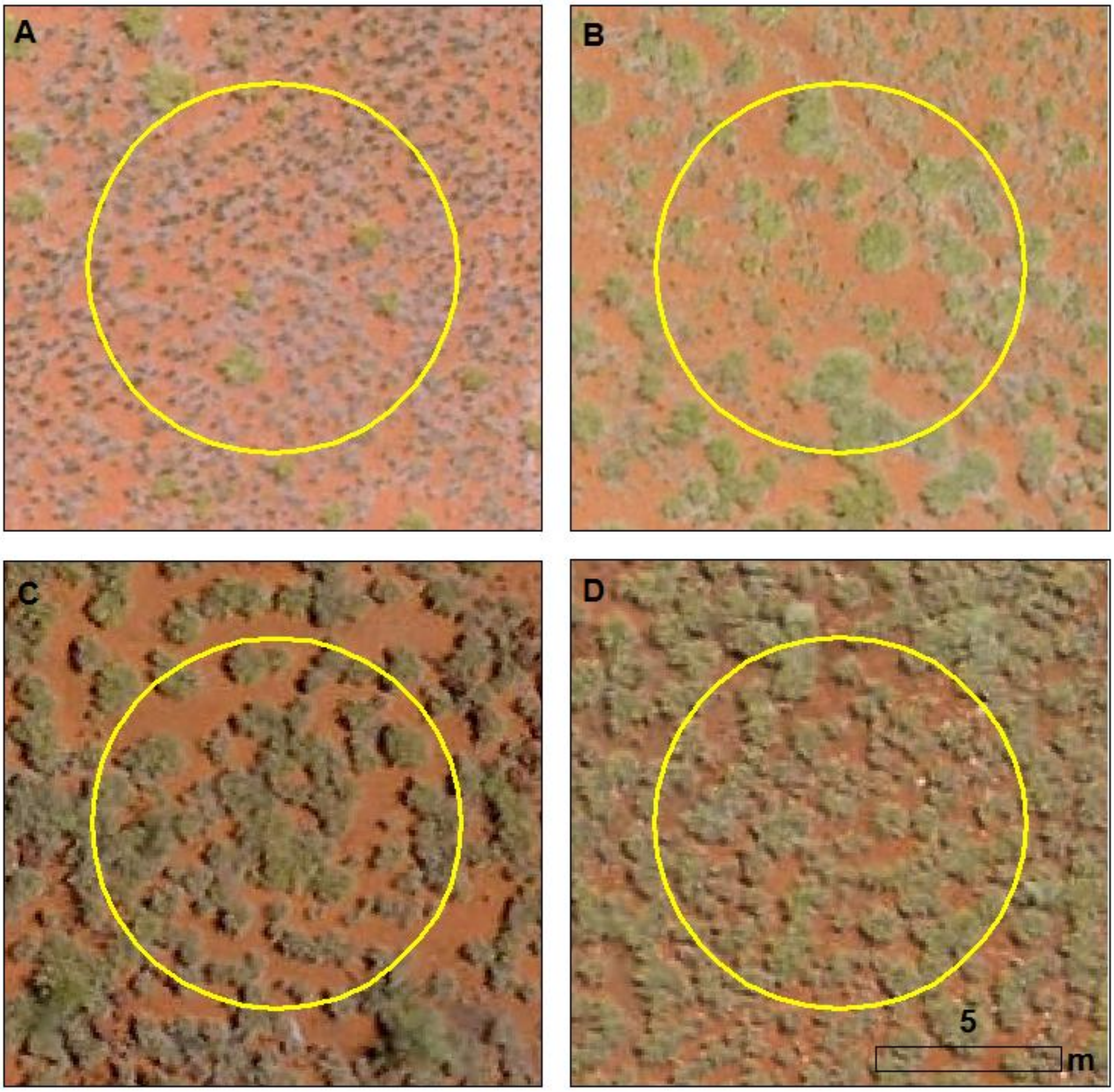

Figure 20 Buffel grass as observed in the field at low 0-25% (A), low –moderate 25-55% (B), moderate – high 55-85% (C) and high >85% (D) projected cover. The dominant grasses in panel A are *Aristida* sp.

5.1.6 Four-band imagery classification

To exploit the additional spectral information in the multispectral imagery, the NDVI was applied. In the desert environment in which our study is situated, Buffel grass is often the ‘greenest’ vegetation in the understorey during the summer months (December to February). Hence, the NDVI is a suitable index to identify cover type. The NDVI output was visually compared with the higher resolution aerial photography to identify an NDVI threshold that best represented Buffel grass cover. The total area classified as Buffel grass was then calculated for each site.

5.1.7 Comparing classifications

To explore differences between each of the cover estimation approaches (visual cover estimates, manual digitisation, unsupervised classification, NDVI thresholds), classification results for selected sites were viewed concurrently and disparities were described. The effectiveness of each approach in quantifying Buffel grass cover was then examined using regression analyses. The four image classifiers were compared not only with the field-based estimates, but with each other, to compare like with like. This is important, because whilst Buffel grass presence-absence is best interpreted from field results, field cover-estimates are also subjective, and not necessarily more correct than the image-based estimates. The strength of each relationship was interpreted using Pearson's *r*-squared.

5.2 RESULTS

5.2.1 Buffel grass in the landscape

Buffel grass is observed to be widespread throughout our study site. It is particularly prevalent in riparian land systems (Figure 21, panel F) and alluvial plains (Figure 21, panel A). In Buffel grass monocultures, on the plains comprised of undifferentiated alluvial and fluvial soils, Buffel grass tussocks are typically encircled by a ring of bare soil (Figure 21, panel B), which is not seen in this land system in patches of native grasses (e.g. Aristida, Enneapogon). In the Tomkinson Ranges, Spinifex is dominant on the hill slopes (Figure 21, panel C), but in the depressions, valleys and the crevices of rock outcrops, Buffel grass is frequently observed. This is also true for the ranges directly north of Kalka (Figure 17). Similarly, on calcareous flats, where Spinifex dominates with minor components of Compositae, and Ptilotus sp. (Figure 21, panel D), Buffel grass was observed in micro-depressions over 0.5 kilometres away from any roadsides. On hills in the north west of this study area, Enneapogon sp. and Buffel grass often co-dominate (Figure 21, panel E). These key land systems within the study area are represented on the panel of photographs presented in Error! Reference source not found.**.**

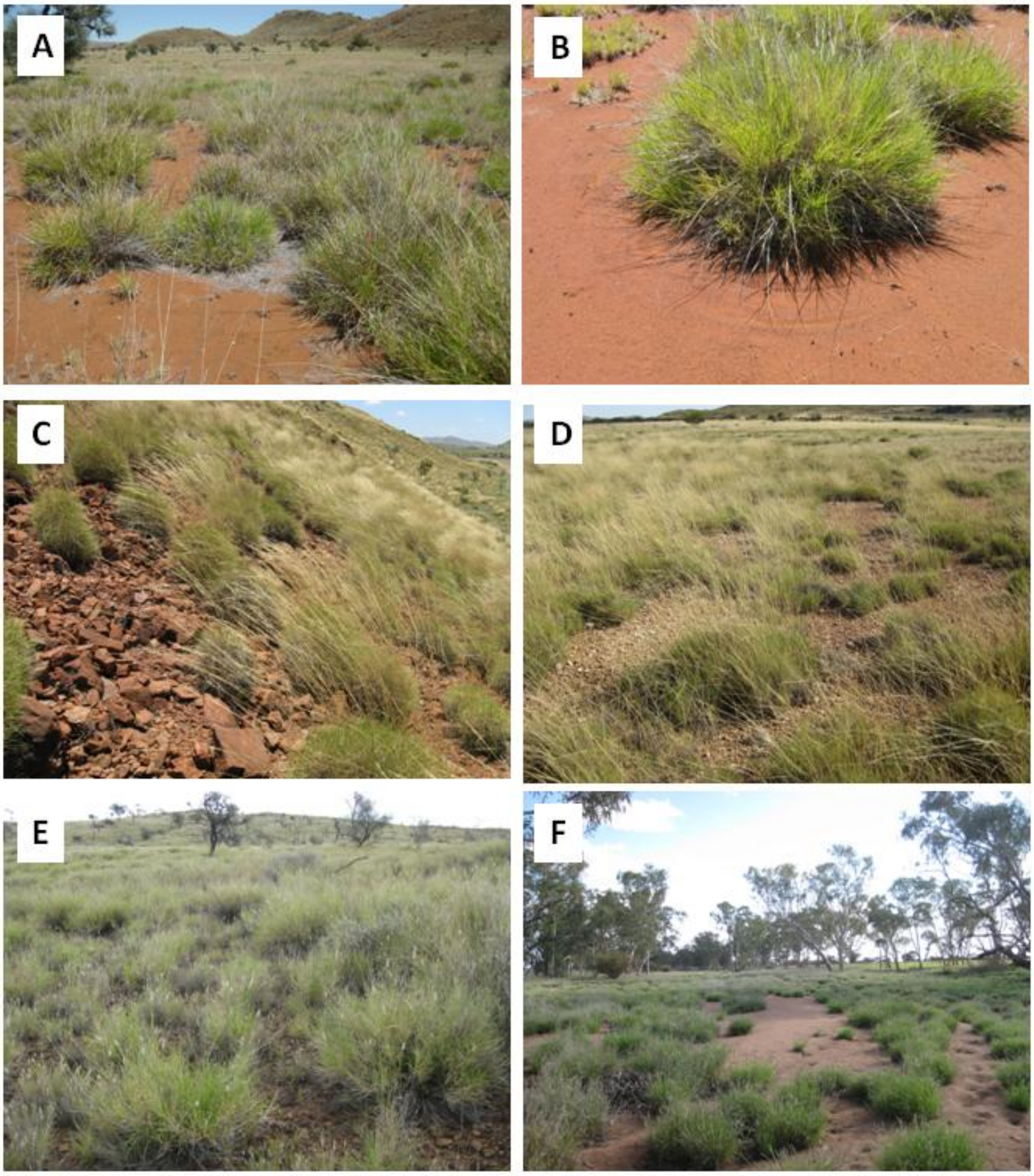

Figure 21 Examples of the dominant landscapes within out study area. Buffel grass dominated alluvial plain (A); mature Buffel grass tussock on alluvial plain, with bare soil surrounding it (B); Spinifex dominated hill slope (C); Spinifex dominated calcareous rubble plain (D); Enneapogon intermixed with Buffel grass on ridge top (E); Buffel grass dominated drainage line (F). Photographs captured February 2012.

Projected cover at each site, as recorded in the field, illustrates the diversity of ground cover within which Buffel grass occurs (Figure 22). There is a general trend that as “Buffel grass” increases, “other grasses” decrease; this is evident in Figure 6. The figure also shows that “soil” cover type is present at all Buffel grass sites. This is consistent with field observations that in Buffel grass monocultures, the tussocks were typically surrounded by bare soil.

Figure 22 Projected cover and composition of 54 field sites in the Kalka-Pipalyatjara region of far north-west South Australia. Cover types were categorically recorded as "Buffel grass", "soil", "woody vegetation", "herbs and forbs" and "other grasses". Projected cover was categorically recorded for each cover type as "0-25%", "25-55%", "55-85%" and ">85%". This graph shows the proportion of projected cover represented by each cover type for each field site.

5.2.2 The imagery

The capacity of colour digital photography (5-6 cm GSD), and four-band Spec Terra multispectral imagery (25 cm GSD) for use in detecting Buffel grass was explored. In the aerial photography it is possible to identify Buffel grass plants as small as 0.3 m in diameter. Larger, more mature plants ranging 0.8- 2 m in diameter are easily discriminated. For large plants, the mixture of dry and green leaves, as well as shadows within the tussocks, are visible. This creates a texture, which in this landscape is quite unique to Buffel grass. In the four-band imagery, much of the internal texture of the plants is lost. Smaller plants, less than half a metre in diameter are difficult to positively identify. Larger tussocks can be discriminated, but out of context, based on spatial information alone, they appear very similar to low shrubs. The near-infrared band was useful for discriminating Buffel grass from native Spinifex where spatial information was inadequate. The NIR band was inadequate for discriminating Buffel grass amongst native bunch grasses, such as Silky brown top (*Eulalia aurea*), Silky blue grass (*Dichanthium sericeum*), Windmill grass (*Chloris* sp.*)* and Barley Mitchell grass (*Astrebla pectinata*).

5.2.3 Comparing projected cover estimates

Four approaches to estimate Buffel grass cover on aerial imagery were trialled: visual cover estimates, manual digitisation, an unsupervised pixel-based classification and NDVI thresholds. Figure 23 illustrates the results of the four classification methods for three ground validation sites, representative of the varying vegetation and geological settings in which we attempt to discriminate Buffel grass. Site 30 (Figure 23, row 1) shows a mono-culture of Buffel grass on red sand, typical of Buffel grass dominated alluvial plains. Site 75 (Figure 23, row 2) represents a transition zone from Buffel grass on alluvial plains to Spinifex hummock grass on a rocky hill slope. At this site, Buffel grass is intermixed with *Aristida* sp. and Compositae sp. Site 6 (Figure 23, row 3) shows Buffel grass growing at high density along a dry creek bank, intermixed with low densities of other grasses such as *Themeda* sp. and *E. aurea*, which is typical of Buffel grass in creek lines.

These examples highlight some of the strengths and weakness of each classification method. Field and image estimate scores at site 6 and 75 are equal, but at site 30, in the Buffel grass monoculture, the field estimate is one point higher than the image estimate. Considering manual digitisation, boundaries are difficult to define where canopies are touching, as evident in site 75 where a grassy mass has been categorised as Buffel grass. Boundaries are also difficult to digitise where the plants are too small, this may be the case at site 6, where there are some newly emerging grasses not circled. The unsupervised classification has a “salt and pepper” effect caused by spectral differences between green and dry foliage within the tussocks and the similarity of Buffel grass with surrounding vegetation. It does not capture the entirety of the projected cover of the grass tussocks as discrete objects. This is evident at all three example sites, but particularly at site 75, where patches of Spinifex are classified as Buffel grass. However, when the sum of the classified area is averaged out across the site the estimates are more comparable to field-based scores. Projected cover estimates based on NDVI thresholds, using the 25 cm GSD multispectral imagery, substantially under-represent Buffel grass.

The relationship between each classification approach was assessed using regression analyses. Every combination of classification approaches was compared, totalling 10 separate regressions, displayed in Figure 24. The strength of each relationship was interpreted using Pearson's *r*-squared. R-squared values based on the four-band imagery (NDVI thresholds) are not statistically comparable with photography-based analyses because the *n* values are different. However, the trends are comparable, and for this reason we have presented all the regressions together. Cover, where Buffel grass was present (field cover ranking =1-4), was comparatively lower in all image-based classification approaches compared with field-based estimates. Where it was absent (field cover ranking = 0), the visual cover ranking and the unsupervised classification were comparatively higher than field estimates, while manual digitising and NDVI thresholds seem consistent. Image visual cover rankings are highly correlated (r^2=0.66) but consistently lower than corresponding manually digitised areas. Pixel-based methods (NDVI and unsupervised classification) tend to over represent Buffel grass absence and under represent presence.

Of all aerial photography image-based classifications, the visual cover ranking best correlates to results collected in the field (r^2 =0.39). Manually digitised area consistently under represented Buffel grass compared with other methods; it returned a highly variable r^2 ranging 0.26 – 0.66. The high-end r^2 (0.66) relates to its correlation with image visual cover rankings. The unsupervised classification correlated moderately well across the board (r^2 ranging 0.21-0.36). The NDVI thresholding approach used to classify the four-band multispectral imagery returned low ranging r^2 values of 0.13-0.27 and under represented Buffel grass projected cover across the board.

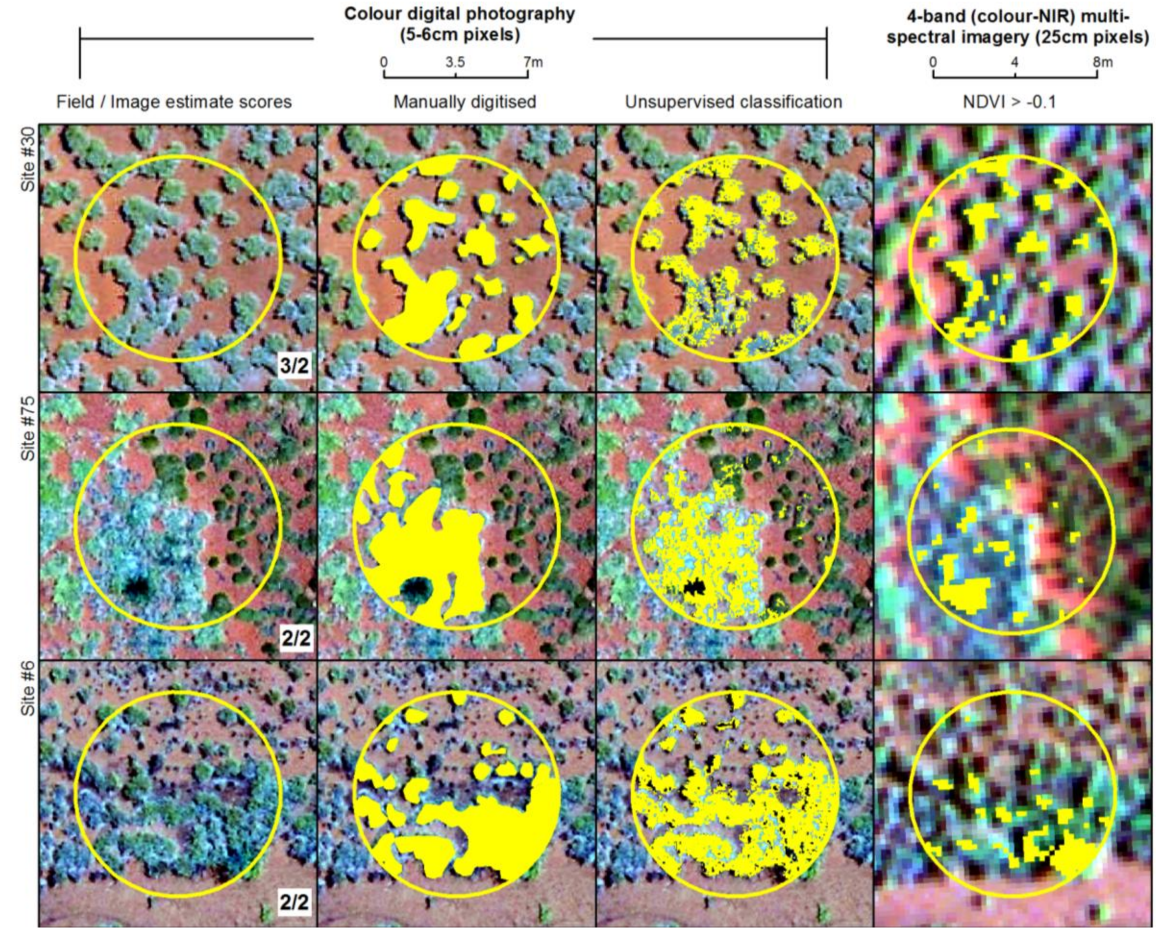

Figure 23 Buffel grass projected cover (yellow) as estimated in the field and on the imagery using visual cover ranking, manual digitisation of plants, unsupervised classification, and NDVI thresholding, for three selected sites (field sites: 30, 75 and 6). Columns 1-3 contain the colour aerial photography (~5cm GSD), and display estimates based on this imagery. Column 4 contains the four-band multispectral imagery (25 cm GSD), natural colour display, and the cover estimates based NDVI threshold. Field / Image estimate scores represent cover as "absence" (0%) = 0, "low" (0-25%) =1, "moderate-low" (25-55%) = 2, "moderate-high" (55-85%) = 3 and "high" (>85%) = 4.

The relationship between each classification approach was assessed using regression analyses. Every combination of classification approaches was compared, totalling 10 separate regressions, displayed in Figure 24. The strength of each relationship was interpreted using Pearson's *r*-squared. *r*-Squared values based on the four-band imagery (NDVI thresholds) are not statistically comparable with photography-based analyses because the *n* values are different. However, the trends are comparable, and for this reason we have presented all the regressions together. The cover, where Buffel grass was present (field cover ranking =1- 4), was comparatively lower in all image-based classification approaches compared with field-based estimates. Where it was absent (field cover ranking = 0), the visual cover ranking and the unsupervised classification were comparatively higher than field estimates, while manual digitising and NDVI thresholds seem consistent. Image visual cover rankings are highly correlated

(r^2=0.66) but consistently lower than corresponding manually digitised areas. Pixel based methods (NDVI and unsupervised classification) tend to over represent Buffel grass absence and under represent presence.

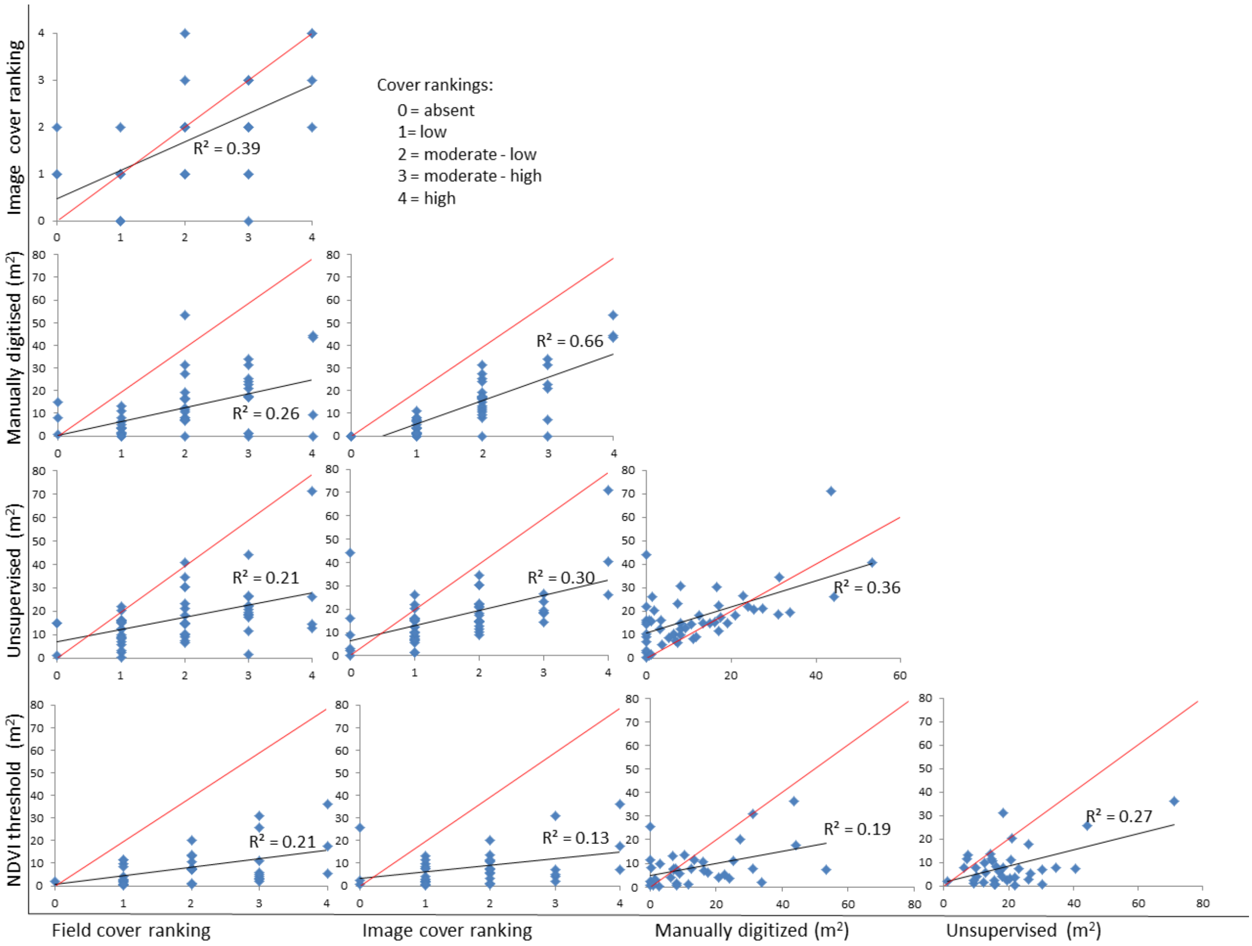

Figure 24 Relationship between each method for estimating Buffel grass projected cover on the imagery (visual cover classes, manual digitising and unsupervised classification and NDVI threshold) and relative to field-based estimates. The strength of those relationships is represented by Pearson's *r*-squared, presented on each graph. Projected cover ranking 0-4 represent "absence" (0%), "low" (0-25%), "moderate-low" (25-55%), "moderate-high" (55-85%) and "high" (>85%) cover, respectively.

Of all aerial photography image-based classifications, the visual cover ranking best correlates to results collected in the field (r^2 =0.39). Manually digitised area consistently under represented Buffel grass compared with other methods; it returned a highly variable r^2 ranging 0.26 – 0.66. The high-end r^2 (0.66) relates to its correlation with image visual cover rankings. The unsupervised classification correlated moderately well across the board (r^2 ranging 0.21-0.36). The NDVI thresholding approach used to classify the four-band multispectral imagery returned low ranging r^2 values of 0.13-0.27 and under represented Buffel grass projected cover across the board.

5.3 DISCUSSION

Buffel grass is an invasive tussock grass widespread in arid and semi-arid ecosystems of Australia and the Americas, which homogenises landscapes, and is a tremendous fire hazard and threatens environmental and cultural values of infested regions. New infestations are where control efforts need to be focused. For control to be successful these emerging infestations need to be detected with improved efficiency. We explored the potential of airborne imagery (ultra-high resolution colour digital photography and four-band visible-NIR) for detection of emerging Buffel grass populations in Australian arid lands. We also compared common image classification techniques (visual estimates, manual digitisation, unsupervised and NDVI thresholding) for their suitability for discriminating Buffel grass.

5.3.1 Buffel grass in Kalka-Pipalyatjara

Buffel grass is observed wide spread in the Kalka-Pipalyatjara region throughout our study site. Alluvial flats, once carrying a diversity of Compositae and Solanaceae members, as well as *Aristida,* and *Enneapogon* species, are now Buffel grass dominated. This is consistent with our breakdown of projected cover at each field site, which showed a general trend of decreasing “other grasses” relative to increasing Buffel grass. In Buffel grass monocultures, on this soil type, individual tussocks are typically encircled by a ring of bare soil. We speculate that this relates to competition for water, preventing establishment of other grasses. On calcareous flats, where Spinifex dominates, Buffel grass was observed in micro-depressions over 0.5 km away from any roadsides, which are often a point of establishment for this invasive species (Lonsdale 1999; Van Devender et al. 2006). Similarly, on Spinifex dominated hills, Buffel grass occurs in the depressions, valleys and the crevices of rock outcrops. On hills in the north west of this study area, *Enneapogon* sp. and Buffel grass often co-dominate although Buffel grass has higher coverage in the creek lines through these hills. In the valley, captured by the south multispectral image, Buffel grass dominates; it is intermixed with native species at the heart of the water course, dominates with bare ground closer to the hills, and gives way to Spinifex on the slopes.

5.3.2 The imagery

Colour digital photography (5-6 cm GSD), and four-band Spec Terra multispectral imagery (25 cm GSD) were compared for their capacity to discriminate Buffel grass, at the individual tussock level, in an open arid landscape.

The 5 cm GSD aerial photography was excellent for visually identifying moderate to large Buffel grass tussocks. The structural detail within the grass tussocks is only visible at the ultra-high resolution. This textural feature in the imagery made visual cover estimates easier. The GSD of 25 cm was too coarse to reveal this distinctive texture and out of context, large tussocks could be misidentified as small shrubs. Small tussocks were indistinct to the human eye at this resolution.

Discriminating Buffel grass is most challenging when the tussocks are densely compacted, with canopies touching or when it is tightly intermixed with other species. One of the reasons for this is that the most distinctive feature of Buffel grass, for the human eye to detect, is its form. It appears as this highly textured unit, in a tight envelope of dead leaf litter, and situated in a ring of bare ground. In fact, where a Buffel grass infestation has expanded to as few as three-four mature (>1 m diameter) plants, this texture can be seen, even on viewing an image frame at its full extent. When these elements cannot be used to identify the grass, even at this very high spatial resolution, greater spectral resolution is needed.

In the NDVI thresholding classifications, we did not find the NIR band particularly helpful to distinguish Buffel grass from other bunch grasses such as Barley Mitchell grass (*Astrebla* sp.) and Silky-brown-top (*E. aurea).* The NIR band may have proved more useful had the grass been at its greenest; Buffel grass was approximately 50% dry and50% green at the time of image capture. Timing dependence is a weakness of classifications reliant on the NIR band. In this case, the added spectral band does not compensate for the coarser GSD.

5.3.3 Classification approaches

Four approaches to estimate Buffel grass cover on aerial imagery were trialled: visual cover estimates, manual digitisation, an unsupervised pixel-based classification and NDVI thresholds. Differences between the classification outputs were visually compared, and the relationship between each classification approach was assessed using regression analyses with Pearson's *r*-squared.

When compared to the field estimates of cover, visual cover ranking was the best performing image-based classifier (r^2 0.39).While perhaps the most subjective method, it is excellent for rapid assessment by a trained image interpreter. Its strength lies in the interpreter's ability to score sites rapidly and adjust interpretation according to context: image quality, vegetation condition and landscape position.

Manual digitisation of Buffel grass infestations was extremely laborious and consistently under represented Buffel grass projected cover compared with all other estimation methods. Image quality is paramount to success in digitising, because slight image blur makes it extremely challenging for the digitizer to identify boundaries. Furthermore, at the individual plant level, boundaries are particularly difficult to define for small plants and for plants with canopies touching. Although it may be beneficial for the natural resource managers to have distribution information digitised, this methodology is still subjective.

The unsupervised pixel-based classification has more potential than the r^2 of 0.21 suggested. It typically underestimated cover. However, it could be just as easily over-estimate cover if more "dry grass" classes were included in the producer's classification of Buffel grass. The method is reliable, systematic and repeatable; however, the process of aggregating classes' representative of Buffel grass was time-consuming when repeated for every field site. The method would be more feasible if the unsupervised classification could be applied to an entire image frame, but with aerial photography this is challenging. Variable sun-angle on the camera, resulting from aircraft tilt as it navigates topography and weather at very low altitudes (305 m, in this case), causes hot spot effects, or overexposure on sun-side edges of the imagery. This results in spectral variation of the same land-cover types across the image frame.

NDVI thresholds had potential to be a strong indicator of Buffel grass cover in this landscape. The methodology is systematic, reliable, repeatable, and rapid because it can be carried out for the entire image frame. We hypothesised that a high NDVI threshold should exclude native grasses and isolate Buffel grass which is highly photosynthetically active following summer rains. However, at the time of image capture in this study, Buffel grass had already begun to dry out, and tussocks were only about

50% green. At this time, woody vegetation had, on average, a higher NDVI than the understorey, and the NDVI values for Buffel grass were not substantially different from surrounding grasses. We chose to set a high NDVI threshold, which underrepresented Buffel grass, rather than a lower NDVI threshold, which would have captured all green vegetation. Timing dependence is a weakness of this classification method, and given the fickle nature of the species' lifecycle, it is not recommended for this scale of mapping

5.4 CONCLUSIONS

Ultra-high resolution, 5 cm GSD aerial photography has potential for regional documentation of new and emerging infestations of Buffel grass. Visual cover rankings performed by an informed image interpreter are currently the most accurate method of classification. These can be conducted quickly and easily, and could be expanded over a larger area with a well-designed sampling strategy to document infestations long before they are seen in the field.

For regional documentation of new and emerging infestations of Buffel grass, we recommend the following approach: (1) collect transects of aerial imagery across the region of interest. Imagery should be colour digital aerial photography with a GSD of 5 cm; (2) using the aerial photos as samples across the landscape, have a trained observer score Buffel grass cover against visual standards; and (3) use the scored sites to interpolate density across the region, target field survey and direct control efforts.

For surveillance of waterways and environments where Buffel grass is known to grow at high densities intermixed with other species, a 5 cm GSD colour digital photography together with airborne hyperspectral imagery could be considered for improved spectral separation, and this is one area for future research.

5.5 ACKNOWLEDGEMENTS

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Chapter Six

Conclusions

6.0 INTRODUCTION

Buffel grass (*Cenchrus ciliaris L.*) is grown widely in tropical and sub-tropical arid rangelands around the globe because of its high drought tolerance and capacity to withstand heavy grazing. However, in certain situations, particularly in arid to semi-arid environments, Buffel grass has the ability to rapidly invade the surrounding environment. Consequences of invasion can be significant as Buffel grass alters wildfire regimes and displaces native flora and fauna. Effective, strategic control of Buffel grass invasions requires understanding of the species' ecology, knowledge of the distribution, and an ability to predict its spread. Methods of survey and detection including tools for ongoing monitoring will also be required.

For rapid assessment at regional scales roadside survey is a common approach to mapping (Rahlao et al. 2010) and is particularly effective for invasive species because roadsides are susceptible to invasion and are accessible to surveyors (Reese et al. 2005). However, for these reasons, roadside survey data are inappropriate for extrapolating predictions about habitats prone to invasion away from the roadside (Reese et al 2005).

Field-based mapping is only feasible over localised areas. Often it is restricted by road access, or to localised areas of particular significance. These areas are mapped with a view to controlling within this area, without intent to monitor invasion over time, and there is usually some prior knowledge of the distribution before localised mapping efforts are undertaken. In the remote desert landscapes of Australia, where Buffel grass thrives and is widespread, field-based mapping is inadequate.

Remote sensing presents possibilities for monitoring invasion in the long term and for early detection of new infestations in remote arid landscapes. However, challenges of remotely detecting a grass, which is spectrally indistinct, growing in stands of unknown extent, and with varied phenology that is a rapid response to rainfall rather than distinctly seasonal are significant. Techniques are not proven for Buffel grass in Australia and thus remote sensing is underutilised by natural resource managers responsible for the control of this invasive transformer species.

The aims of this research were to synthesise international information about Buffel grass invasion ecology that would inform subsequent research, map its current distribution within regional arid Australia with a view to developing a predictive habitat model, assess the feasibility of using roadside survey data for predictive habitat modelling and assess the practicality of using remote sensing to detect new infestations of Buffel grass. These aims have been addressed and the major contributions that this PhD research has made to invasive plant science and management are summarised in the following section.

6.1 MAJOR RESEARCH CONTRIBUTIONS

6.1.1 A new summary of the global ecology, distribution and biodiversity impacts of Buffel grass when behaving as an invasive species

The paper titled *"Buffel grass (Cenchrus ciliaris) as an invader and threat to biodiversity in arid environments: A review"* is the first comprehensive summary of the invasive characteristics of Buffel grass required for effective management and control of the species in invaded landscapes worldwide. Prior to this the majority of information was hidden in agricultural and grey literature focused on improving Buffel grass pasture.

In this literature review, the key environmental parameters which define the fundamental niche of Buffel grass are identified. At a global scale, temperature emerges as the primary factor restricting spread, with the species not surviving at average monthly temperatures below 5 °C (Cox et al. 1988). Emergence is reliant on soil disturbance. As such, regional distribution is likely to be associated with disturbed environments such as creek lines and roadsides. Soil texture and seasonal rainfall influence germination rates, although once established Buffel grass is not selective with regard to these factors. Successful population establishment may depend on appropriate soil texture, availability of nutrients such as phosphorus and nitrogen, topography and sun exposure.

Arid and semi-arid environments are particularly prone to Buffel grass invasion and poorly tolerate the increased frequency and intensity of wildfires that accompany increased biomass of the grass. It is strongly suspected that Buffel grass fuelled fires are responsible for declining numbers of characteristic arid zone plants, the Saguaro Cactus (Arizona, USA) and River Red Gum (Australia). It is concluded that arid landscapes worldwide require urgent control of Buffel grass.

This review highlighted the morphological characteristics, environmental tolerances and biodiversity impacts of Buffel grass to facilitate predictive habitat modelling and identification of regions requiring urgent control. The paper is already impacting emerging scientific literature on the topic with six citations as noted on the 16th of October 2013.

6.1.2 New maps of the current distribution of Buffel grass along roadsides in regional South Australia

Buffel grass roadside survey carried out in May 2010 (Shepherd et al. 2010) in collaboration with Biosecurity SA and Rural Solutions SA provides baseline information and is the most up-to-date record of Buffel grass distribution in regional South Australia at this scale. Survey route selection was informed by opportunistically collected presence data collated from various online and private sources in the months leading up to the survey as a part of research towards this doctorate.

Over 3100km of roads were surveyed over a nine day period. Species presence-absence and density at the roadside ("disturbance zone" in Shepherd et al. (2010)) and away from the road verge on adjacent land ("natural zone" in Shepherd et al. (2010)) was recorded. A dynamic threshold between roadside and adjacent land was defined.

The survey showed Buffel grass was widely distributed along roadsides across regional arid South Australia and mostly at sparse density. Roadside populations were primarily observed along major highways that experience heavy traffic flow around Glendambo and Port Augusta. Adjacent land populations were typically associated with roadside populations. This is consistent with anecdotal observations that the grass enters the state along major highways and spreads out where conditions are appropriate. High density Buffel grass infestations on the adjacent land were all linked to drainage lines.

Results of this survey were used to direct mowing and herbicide treatments of Buffel grass along thousands of kilometres of South Australian road. The methodology has been adopted by Alinytjara Wilurara Natural Resource Management Region for their community mapping projects. Results and methodology were presented at a state Buffel grass workshop held in Port Augusta in May 2011. Outputs from this workshop formed the basis for the State Buffel grass Strategic Plan 2012-2017 produced by Biosecurity SA which was released in October 2012 (Biosecurity SA 2012). The plan develops and promotes the use of three management zones for the state-wide management of Buffel grass: Zone 1, Buffel grass is widespread and management focuses on targeted management of key assets; Zone 2, Buffel grass is widely scattered and spread from established infestations needs containing; Zone 3, Buffel grass is minimally scattered, where feasible, the goal is to eradicate all infestations from this zone.

6.1.3 A new approach to roadside survey that makes the data more relevant to species distribution modelling beyond the road effect zone

In the paper *"Buffel grass roadside survey and invasive species distribution modelling"* a new approach to roadside survey which makes the data more relevant to landscape-wide predictive modelling is developed and trialled with strong results.

The approach requires observers, at the time of survey, to record presence-absence observations at the roadside as separate from those observations away from the road on adjacent land. Survey results demonstrate the importance of actively observing occurrences away from the road, for in 1 in 5 cases, an observation of Buffel grass may not have been recorded by surveyors focussed on the roadside.

Buffel grass occurrence data for roadsides and adjacent land were then considered as separate dependant variables for predictive habitat modelling; separate models were created for the roadside environment and for adjacent lands. It is widely accepted that Buffel grass is spread along roadsides. Thus, for adjacent land we constructed an additional model that included roadside occurrence, as a proxy for propagule pressure in the model.

Across the models the inputs and general trends were almost the same; however, the significance of covariates differs. This suggests that predictive models based on roadside data would correctly identify adjacent land areas at risk, but incorrectly weight level of risk as compared to models based on adjacent land data. The argument to collect both roadside and adjacent land data are strengthened by the inclusion of roadside presence-absence, a proxy for propagule pressure, in the adjacent land model. We found that the propagule pressure covariate substantially improved overall adjacent land model performance and consider that roadside presence-absence was an effective surrogate.

For modelling the exotic distribution of invasive species spread along roadside, we strongly recommend consideration of this approach. Caution is recommended in utilising this type of data for species distribution modelling in very newly invaded sites because observations could be too spatially limited to run effective regression analyses. Another potential limitation of this survey approach is the ability to view the extent of invasion into the adjacent land. In the sparsely vegetated arid landscapes where this study was based, it was largely inconsequential, but it may be a substantially limiting factor in other bioclimatic regions.

6.1.4 A species distribution model for Buffel grass in regional South Australia

Buffel grass distribution models presented in the paper *"Buffel grass roadside survey and invasive species distribution modelling"* (Chapter 3) developed on the basis of 2010 roadside survey (Appendix 1) are the first applicable to arid regional South Australia. Models were run based for data observed at the roadside and on adjacent land; the impact of using roadside-presence absence as a surrogate for propagule pressure in modelling for adjacent land was also considered. Environmental variables considered in the models could be broadly categorised as climate, geology/ landscape, anthropogenic and vegetation.

Propagule pressure emerged as the primary determinant of Buffel grass infestations on adjacent land. The results were consistent with a recent study by Fensham et al. (2013) on Buffel grass invasion of remnant Eucalypt woodland in Queensland, Australia, which showed that propagule pressure had a stronger effect on Buffel grass invasion than both grazing and fire, which are widely believed to facilitate invasion.

The key environmental influence on Buffel grass distribution, as revealed by our modelling, was minimum temperature. This is consistent with ecological understanding of this C4 species, that it prefers warmer temperatures, and cannot establish at low temperatures (< 5 °C) (Cox et al. 1988). Soil texture (clay in the topsoil) was minimally associated with Buffel grass distribution in the models, and was eliminated when propagule pressure was incorporated as a covariate. This was unexpected since several studies suggest that persistence is dependent on specific textural types (Humphreys 1967; Cox et al. 1988; Van Devender et al. 2006). Nonetheless, our results suggest that influx of propagules will be more significant than soil texture on invasion. Drainage lines were significantly associated with Buffel grass infestations, both at the roadside and on adjacent land. Furthermore, we report a positive correlation between the density of infestations and distance to drainage lines. Our findings support global observations that river systems are a major means for the spread of weeds (Johansson et al. 1996)

The models return strong results and on the basis of these management recommendations are made that containment of propagules along roadsides will be the most important factor in preventing spread and that where roads intersect drainage lines should be focal points for monitoring.

The models presented in this paper should not be made spatially explicit without further validation to consider the spatial context of errors. If made spatially explicit, a proximity to roads threshold should be applied to both the roadside and adjacent land models.

6.1.5 Techniques for remote sensing of Buffel grass in arid landscapes

High resolution multispectral satellite imagery and very high resolution aerial photography are trialled for the first time in application to Buffel grass discrimination in heterogeneous arid landscapes of central Australia.

In the study presented in Chapter 4, we explore the use of WorldView-2 satellite imagery, a satellite product with 8 spectral bands across the visible and near-infrared (NIR) and 2 m spatial resolution, to discriminate Buffel grass and test whether it offers a tangible improvement on traditional four-band (visible and NIR) multispectral imagery.

Buffel grass was known to be widespread at high density throughout the study site, located just west of Alice Springs, Northern Territory. The imagery was captured following heavy rains of early summer when all ephemerals were green. Under these circumstances, linear discriminant analysis showed no significant difference in spectral separability of Buffel grass spectra from surrounding vegetation, whether assessed using four or 8 spectral bands. It was concluded that for detecting Buffel grass in late summer in this area, standard four-band multispectral imagery would be adequate.

The classifier (Mixture Tuned Matched Filtering) and threshold applied to the imagery mapped Buffel grass with 59% overall accuracy, as validated in the field. Visual inspection of the image classification showed high density infestations were well detected. It is proposed that WorldView-2 would offer greater potential for the discrimination of Buffel grass under different seasonal conditions. Given Buffel grass rapidly responds to rainfall, the best time for image capture is likely to be following the first big rains at the end of the dry season, when Buffel grass has greatest contrast from the surrounding environment.

For newly emerging infestations it was firmly concluded from this WorldView-2 assessment that higher spatial resolution is required. This was explored in the major study into remote sensing Buffel grass, presented in Chapter 5.

In the Kalka-Pipalyatjara region of far north-west South Australia, we trial the use of very high resolution (25 cm GSD) multispectral four-band (colour-NIR) imagery and aerial photography (5 cm GSD) for detecting Buffel grass infestations across various landscapes and evaluate commonly used classification approaches: visual cover estimates, digitising, pixel-based classifiers (unsupervised classification and NDVI thresholds).

In the desert environment in which this study is situated, Buffel grass is often the ‘greenest’ vegetation in the understorey during the summer months (December - February). However, Buffel grass foliage was 50% dry at the time of image capture, making NDVI values indistinct from surrounding grasses, and NDVI thresholding an ineffective means of classification. Timing dependence is a weakness of this classification method and in this scenario the added spectral resolution did not compensate for a reduction in the spatial resolution.

In a separate assignment we considered the 5 cm GSD aerial photography to be excellent for identifying moderate to large Buffel grass tussocks. This spatial resolution revealed structural detail at the sub-plant level, which contributed to its distinctive texture on the imagery. By eye, it was most challenging to discriminate Buffel grass when the tussocks were densely compacted, with canopies touching or it is tightly intermixed with other species. The reason for this was that the most distinctive feature of Buffel grass, for the human eye to detect, is its form. On alluvial flats and red sands it appears as this highly textured unit, in a tight envelope of dead leaf litter, and situated in a ring of bare ground. Moreover, where a Buffel grass infestation has expanded to as few as three-four mature (>1 m diameter) plants, this texture can be seen even on viewing an image frame at its full extent. When these elements cannot be used to identify the grass, even at this very high spatial resolution, greater spectral resolution is needed.

This distinctive texture made visual cover estimates and digitising easier. Conversely, it presented challenges for the pixel-based classifications. The high level of internal detail, showing dry and green leaves as well as shadows, meant that several of the unsupervised cover classes had to be merged in order to represent the whole plant and the salt and pepper effect of this classification could not be resolved.

To summarise, very high resolution aerial imagery shows great potential for regional documentation of new and emerging infestations of Buffel grass. It will be most worthwhile across remote landscapes, which have minimal access. Visual cover rankings, performed by an informed image interpreter are currently the most accurate method of classification. These can be performed quickly and easily, and could be expanded over a larger area with a well-designed sampling strategy to document infestations long before they are it’s seen in the field. We recommend this approach be adopted for early detection of infestations across open arid landscapes

6.16 New documentation of Buffel grass density across the Kalka-Pipalyatjara region of South Australia

Through the evaluation of aerial photography over the Kalka-Pipalyatjara homelands and extensive field survey we observed and reported Buffel grass to be widespread throughout the Kalka-Pipalyatjara region, most noticeably on alluvial flats. The observations showed a trend for Buffel grass to occur at highest density near creek lines, but interestingly, actually in the creek line, or in the immediate creek banks, native grasses still reside. On calcareous washes, Buffel grass was found to occur primarily in depressions of the micro-topography. Otherwise this landscape was dominated by Spinifex, daisies and *Ptilotus* sp. on the peaks of the ranges separating Pipalyatjara and

Kalka, Spinifex dominates. However, Buffel grass is present. It’s present in the washes, and in the valleys. The ranges in the north-west of the study site gently sloping, extremely rocky, and is widely distributed across them, along with native *Enneapogon* sp.

6.3 RECOMMENDATIONS FOR FUTURE APPLICATIONS AND RESEARCH

Buffel grass is a contentious species of growing concern in Australia and around the globe. Tools needed to mitigate spread include maps of present distribution, techniques for mapping and monitoring invasion over time, and an understanding of the species ecology as an invader to predict regions vulnerable to infestation. These tools were developed and are presented within this thesis. In the process, research was conducted with much broader implications for the management of invasive species, including new methodology for roadside survey that makes the data useable in predictive modelling, and assessments of remote sensing techniques which may be utilised for discriminating invasive tussock grasses in heterogeneous arid landscapes.

One thing that emerged from reviewing literature on Buffel grass was that the species is highly varied, with many varietals exhibiting different environmental tolerances and morphological features some specifically cultivated to withstand frost and drought. However, the impact of these sub-species on understanding invasion success and distribution of Buffel grass is largely unknown. To resolve this, a spatially oriented study into the genetics of Buffel grass populations in Australia would be required. The objectives being to assess whether populations exhibiting different levels of invasion success are linked to the different cultivars and whether there are genetic adaptations within sub-species between populations. Findings would be most important if they identified a need to manage Buffel grass at a sub-species level.

In Chapter 3, we conceptualise models of Buffel grass distribution in arid regional South Australia. These should be explicitly mapped to demonstrate habitats vulnerable to infestation throughout the state, and such maps should be validated. This could be done by repeat surveys over subsequent years, and informed by strong record keeping of any control efforts that have been undertaken along roads included in the survey. Without records of mitigation efforts, it would be worth conducting a survey with stakeholders about the perceived accuracy of the predictive maps. Sites vulnerable to invasion should be assessed according to biodiversity value and feasibility of control then ranked in order of importance for control. This should be done in the context of a cost-benefit analysis important for long term regional control.

Further to this, the roadside survey methodology produced strong results for Buffel grass mapping and modelling and we indicate that it could be considered for use with other road corridor dispersed invasive species. To strongly recommend this approach, the methodology should be trialled with other species and quantitatively examined. This should be considered as a minor study for future research.

Aerial survey conducted over the APY lands has several implications for future management. Firstly, now that methodologies for survey sampling and image classification have been outlined (Chapter 5), the process could be used to explicitly map Buffel grass over the study area. Maps of Buffel grass distribution for the Kalka region would provide important baseline datasets useful for implementing immediate management regimes and for localised predictive modelling. To obtain more detailed environmental parameters than the regional model provided (Chapter 3) this would require collection of new environmental datasets. Secondly, this methodology could be implemented for the entire APY lands. This would be beneficial to APY Land management where invasion is particularly devastating and difficult to access for monitoring, but also for the state, as this region is identified in Zone 1 (Mitigate spread) of the State Management Strategy.

The greatest cost of aerial surveys like the one carried out here is getting the aircraft to location. An emerging popular branch of remote sensing is that of unmanned aerial vehicles (UAV) (Knoth et al. 2013; Lucieer et al. 2013; Tian et al. 2013); digital cameras can be mounted on inexpensive aerial vehicles and operated by non-experts in the field to capture very high resolution quickly and at a low acquisition cost for vegetation mapping purposes (Dandois et al. 2013). It offers great potential for integration as a tool in weed research and site-specific management (Rasmussen et al. 2013), and is worth exploring for Buffel grass.

Ideally, heavily infested regional areas will be monitored using satellite imagery, which is far more cost effective than aerial survey. In the heterogeneous landscapes where this research was conducted, moderate resolution satellite imagery has been inadequate, although in Australia it has not been examined with a temporal dynamic. MODIS and Landsat time series data were useful for monitoring pasture health in Sonoran Desert and we recommend it be trialled in Australia’s pastoral regions.

We show that high resolution satellite imagery like WorldView-2 is promising for monitoring of established infestations. However, the window of time which the provider Digital Globe requires to capture the imagery is approximately 2 months. This is not optimal for capturing Buffel grass during its rapid green-up phase. Remote sensing techniques for monitoring infestations over time are one area where further research is particularly urgent. Satellite sensors with 10 m GSD could be trialled if there is an archive of information available.

6.2 CONCLUSIONS

Overall this thesis contributes to the literature and knowledge of how spatial information science and remote sensing can be used to better understand invasive species ecology and inform management decisions. Specifically, the thesis examines Buffel grass invasion in arid Australia. Comprehensive review of Buffel grass behaving as an invasive species was a critical aspect of this research. This synthesis of current knowledge from agricultural, plant science and grey literature was used to inform all subsequent components of this research and serves as an important aid to other researchers interested in this globally topical species. Development of roadside survey methodology and route selection used to create maps of present distribution (2010) was a considerable process. The final output was used to inform immediate management of Buffel grass in regional South Australia but also to develop and test new methodology for predictive species distribution modelling of invasive species in their exotic range, which is an increasingly important objective of invasive species management. Finally, remote sensing techniques for detecting infestations of Buffel grass in Australian arid lands were developed and trialled with strong recommendations for future use.

Chapter Seven

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Appendix One

2010 Buffel grass roadside survey

Shepherd, B., Marshall, V. (2010) “Buffel grass roadside survey 2010” Dept. Of Water Land and Biodiversity, Rural Solutions SA, Adelaide

The report presented in this appendix was produced for and in collaboration with Biosecurity SA and Rural Solutions SA