The role of fire in coastal dune geomorphology

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Declaration

I hereby declare that this thesis has not been previously submitted to any other institution or university for a higher degree. Except where otherwise acknowledged, this thesis is comprised entirely of my own work.

Samuel Joel Shumack

10th October 2016

This thesis has been formatted to ensure compliance with a page limit of 50 pages for text and figures determined by the Faculty of Science and Engineering at Macquarie University.

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Abstract

After disturbance to protective covering, vegetated sand dunes may become bare and mobile. This thesis addresses the hypothesis that fire is a disturbance which plays a role in de-stabilising coastal dunes. Firstly, we conducted a regional scale remote sensing analysis of Landsat Thematic Mapper, Enhanced Thematic Mapper Plus, and Operational Land Imager data on 31 fire-scars on coastal dunes in Western Australia (WA). We used the Normalised Difference Vegetation Index to assess medium-to-long term vegetation recovery and maximum-likelihood image classification to monitor substantial changes in bare sand area. Secondly, we surveyed recently burnt coastal dunes near Esperance to characterise the disturbance to the dunes' protective covering in terms of remnant vegetation structure, wind flow, surface characteristics, aeolian activity, and regeneration. Results suggested that a) no active dunes were initiated by 30 fires over 28 years; b) native dune vegetation regenerates well after fires, particularly within six months; c) burnt vegetation allows wind to impact the surface with minimal obstruction, but may not allow the same topographic acceleration seen on active dunes; d) remnant ground cover inhibits post-fire sand movement; and e) complex interactions between burn severity, seedbank distribution and post-fire precipitation affect regeneration, and may prolong surface exposure to wind.

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Chapter 1 – Introduction

1.1 Background

Coastal sand dunes are important and diverse environments. Globally, they provide numerous services including habitat for endangered species, groundwater recharge, and protection against storm surges (Everard et al., 2010). They are also used for military activities, recreation, mineral extraction, grazing, and cropping (Lithgow et al., 2013). Geomorphically, coastal sand dunes are complex features. They exist in a range of states between mobile, with abundant sand movement by wind (aeolian activity), and stable, with a protective covering (vegetation, soil etc.) limiting sand movement (Fig. 1.1) (Arens et al., 2007). Broadly, the state of dunes and their form is controlled by the available sediment, wind regime, and the growth capacity of vegetation (Arens et al., 2007). Within this framework, complex feedbacks between these parameters and the added influence of disturbances means dunefields can transition between states of activity and stability, or simultaneously experience stability with localised areas of activity (Yizhaq et al., 2013). For example, disturbance involving the removal of vegetation cover locally or regionally (e.g. by fire or stock grazing) may leave the sand surface susceptible to erosion by wind (Levin et al., 2012; Barchyn and Hugenholtz, 2013). Post-disturbance movement of sand may occur to some degree with little net surface change and with the dune remaining largely stable (Vermeire et al., 2005). However, this deflation may in turn suppress further vegetation growth, and the resulting continuance erosion may begin to form blowouts (Barchyn and Hugenholtz, 2012b; 2013; Yan and Baas, 2015). When a blowout (an erosional hollow with a downwind depositional lobe or apron) develops, the dune may be considered destabilised or re-activated (Barchyn and Hugenholtz, 2013). Blowouts may begin to migrate, eventually forming new, often parabolic-shaped, dunes (Barchyn and Hugenholtz, 2013; Hesp, 2013).

Thus, with adequate disturbance to protective cover, combined with appropriate meteorological conditions, stable or vegetated sand dunes may destabilise into an active state with little or no protective covering (Barchyn and Hugenholtz, 2013). However, not much is known about the likelihood of various disturbances resulting in de-stabilisation (Barchyn and Hugenholtz, 2013). This thesis will test the hypothesis that fire is a disturbance which plays a role in destabilising coastal dunes.

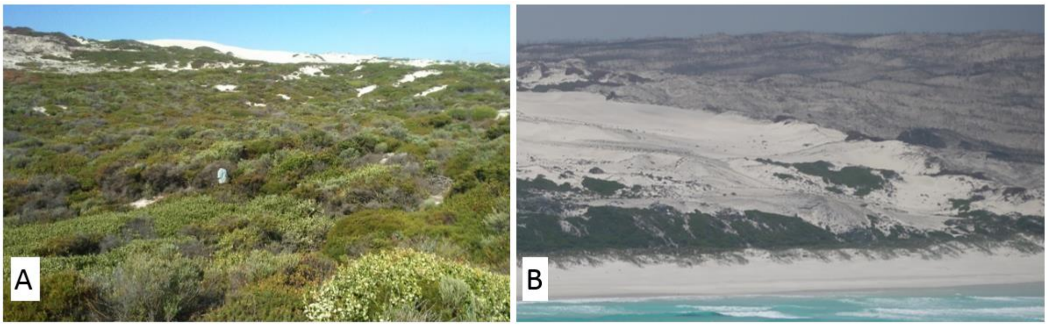

Figure 1.1 Coastal dunes near Esperance, WA. (A) Stable and vegetated, Photo Samuel Shumack; (B) Active blowout (middle ground) and burnt coastal heath covering sand dunes (background). Photo Paul Hesse

1.2 Fire as a disturbance

Fire is often listed among the possible disturbances leading, or contributing to dune de-stabilisation (Conacher, 1971; Martini, 1981; Christensen and Johnsen, 2001; Catto et al., 2002; Wiles et al., 2003; Lepczyk and Arbogast, 2005; Buynevich et al., 2007; Barchyn and Hugenholtz, 2013; Yizhaq et al., 2013; Ruz and Hesp, 2014). The recurrence interval of fires for coastal heathlands varies between 3 and 20+ years, depending on species composition, climate and human activities (Russell-Smith et al., 2007). Little is known of the effects of such fires on coastal dune systems (Vestergaard and Alstrup, 2001). Greater understanding would be valuable for land managers planning hazard reduction burns over vegetated coastal dune areas, and may also be helpful for identifying areas to target for post-fire assisted rehabilitation. Understanding the effects of fires also has implications for the management of dune areas being used for stock grazing, recreation, and military activities (Catto, 2002; Levin and Ben-Dor, 2004; Thompson and Schlacher, 2008). Barchyn and Hugenholtz (2013) note that an understanding of de-stabilisation processes has particular importance because de-stabilisation is generally considered a form of land degradation. While acknowledging that benefits exist for maintaining active dune areas (e.g. ecological niche environments, groundwater recharge etc.), there are significant concerns regarding de-stabilisation. These include the loss of sand within the coastal sediment budget, and loss of productivity in aeolian landscapes used for agriculture (Arens et al., 2007; Harper et al., 2010; Barchyn and Hugenholtz, 2013; Lithgow et al., 2013).

1.3 Observing medium to long term response

There is some evidence suggesting fires have led to dune deflation in the past. Throughout the subarctic boreal regions of the northern hemisphere, dunes appear to have been activated to some degree after forest fires during the Holocene. Studies in Alaska, Canada and Finland (Filion, 1984; 1987; Filion et al., 1991; Seppala, 1995; Kayhko et al., 1999; Mann et al., 2002; Carcaillet et al., 2006; Matthews and Seppala, 2014) and further south in Lithuania (Gaigalas and Padzur, 2008) have shown sequences of charcoal layers followed by sand deposits, inferred to mean that the fire producing the charcoal also exposed bare sand and allowed deflation. The presence of localized charcoal layers of varying thicknesses supports a model of patchy deflation following fires involving (Matthews and Seppala, 2014):

- Erosion (where charcoal is not preserved);
- Deposition (where charcoal layers are preserved); and
- The remaining surface being preserved by mosses or lichen and without aeolian activity (where charcoal can then build up into a thicker layer over several fire events).

Others studying the Holocene history of dune areas (e.g. Martini, 1981; Wiles et al., 2003; Lepczyk and Arbogast, 2005; Buynevich et al., 2007; Ruz and Hesp, 2014), have cited this literature in support of suggestions that fire could have been a driver of activity, though they did not show the same charcoal layering. More recent histories in coastal regions have been documented, referring to local reports of dune activity and blowout formation after burning, but without empirical observations (Stockton, 1982; Smale, 1994; Christensen and Johnsen, 2001).

The use of the recorded charcoal layering in dunes as evidence for post-fire de-stabilisation is questionable for two reasons. Firstly, there appear to be no recorded first-hand observations of post-fire dune de-stabilisation to support the interpretation of charcoal layering, despite the apparent plausibility of the interpretation. Secondly, if the interpretation is correct, the occurrence seems restricted to specific environments (notably, pine-forested dunes in cold climates). For example, the same dense layering has not been documented in the world's temperate coastal dune systems. It remains unclear what role fire plays in the formation of the many active coastal dunes. Thus there is a need for real-time observation of the medium-to-long term response of coastal dunes to fire across numerous case studies.

1.4 Assessing disturbance from fires

In the months and years following a fire event prior to regeneration of ground cover, the surface is exposed and susceptible to erosion by wind. Several studies monitoring post-fire soil erosion have recorded substantial increases in saltation after fires on grasslands (Zobeck et al., 1989; Sankey et al., 2009a; 2009b; Ravi et al., 2012; Stout, 2012) and on dunes (Whicker et al., 2002; Vermeire et al., 2005). However, the hypothesis that post-fire erosion on dunefields may develop into blowout features has not been adequately tested. The same studies which showed increased erosion rates, also typically showed eventual vegetation recovery without de-stabilisation within their respective study periods (Zobeck et al., 1989; Whicker et al., 2002; Vermeire et al., 2005; Whicker et al., 2006; 2009b; Sankey et al., 2009a; Ravi et al., 2012; Stout, 2012). There is a need for better characterisation of the disturbance to coastal dunes from fires in terms of post-fire aeolian activity. While post-fire aeolian activity is common, there are several unanswered questions about the nature of dune disturbance after fires: Do fires sufficiently disturb the protective covering to increase sediment availability and allow substantial movement of sand by wind? How does burnt vegetation interact with wind? How do fires affect vegetation growth capacity on dunes?

1.5 Research aims

This thesis addresses the question 'what is the role of fires in enhancing aeolian activity on coastal dunes?'. The chosen study sites for this research are coastal dune fields in south Western Australia (WA). The question will be addressed with two draft journal papers. The papers and their aims are:

1. 'The impact of fire on sand dune stability: surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016'
   - (i) Observe the medium to long term pattern of vegetation recovery after fires on Western Australian coastal dunes
   - (ii) Identify regional influences on recovery from precipitation rates and fire characteristics

(iii) Monitor changes in bare sand area in response to fires

2. ‘Characterising the disturbance from fires on coastal dunes near Esperance, Western Australia: implications for dune de-stabilisation’
    (iv) Characterise the impact of fire in terms of the disturbance to protective covering on dunes
    (v) Compare wind-flow over vegetated, burnt and bare surfaces
    (vi) Compare surface characteristics of vegetated, burnt and bare sites and identify interactions between surface characteristics, wind flow, and aeolian activity
    (vii) Identify local patterns in vegetation recovery and implications for potential de-stabilisation

1.5 Thesis structure

This chapter provides the background for this thesis and its key aims. The following two chapters are draft papers intended for submission to different journals. The first paper is titled ‘The impact of fire on sand dune stability: Surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016’. This is formatted as a stand-alone journal article and includes introduction, materials and methods, results, discussion, and conclusion sections. For this paper, the chosen method is a multi-site assessment of open source multispectral satellite imagery, combined with analysis of available meteorological data. The study involves a time-series remote sensing analysis of coastal dune sites where fires have taken place. We track trends in post-fire vegetation recovery and bare sand area. Burn severity and post-fire precipitation are also assessed to identify possible influences on recovery patterns. The intention is to address the thesis question at a regional scale in the medium-to-long term.

The second paper is titled ‘Characterising the disturbance from fires on coastal dunes near Esperance, WA: implications for dune de-stabilisation’. This has also been formatted as a stand-alone journal article with introduction, materials & methods, results, discussion, and conclusion sections. This paper uses recent fires on coastal dunes near Esperance, WA as a case study for a detailed assessment of post-fire disturbance. The paper documents a field-based study characterising and quantifying the post-fire environment in terms of remnant protective cover, its roughness effect on wind velocity, and evidence of post-fire aeolian activity. Having previously addressed the thesis on a broad scale, the intention in this paper is to examine fires on dunes at a process scale in the short term. The goal is to understand fire-related geomorphic processes in order to better interpret the pattern of response across Western Australian coastal dunes.

Chapter four will conclude the thesis by summarising the outcomes of the research and framing them within the broader context. Directions for future research in this area will then be highlighted.

Due to the nature of thesis-by-publication, some minor overlap and repetition is expected between chapters. Each paper, however, has a distinct focus.

Chapter 2 – The impact of fire on sand dune stability: surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016

Purpose: This chapter presents original research that has been undertaken entirely within this MRes year. The chapter provides an introduction, methods, results and discussion related to the vegetation recovery and geomorphic response of coastal dunes in Western Australia (WA) after fires. There has been limited geomorphic research into the impacts of fires on temperate or sub-humid coastal dune systems. This broad analysis of coastal dune response to fire across two regions of WA, monitors the common response in terms of patterns of vegetation recovery and possible post-fire increases in areas of bare surface. This chapter will address aims i, ii, and iii highlighted in the introductory chapter.

Format: In accordance with the Macquarie University policy for higher degree research thesis by publication[1] this chapter has been written for submission to a peer-reviewed journal (*International Journal of Wildland Fire).* Repetition and any referencing and stylistic inconsistencies have been minimised to facilitate the thesis examination process. Supplementary material and references referred to in the paper are provided in the reference list and appendices at the end of the thesis, and are intended to become the references and supplementary material provided in the published version of this paper.

Author contributions: The authors of this paper and their contributions are as follows:

Samuel Shumack obtained imagery and carried out image processing and data extraction, conducted mapping, analysed and interpreted data, designed and drafted all figures and tables, and wrote and edited the paper.

Paul Hesse developed the study with S.S., designed some figures with S.S., provided comments on the paper, and supervised S.S. in the research.

Other significant contributions to the paper:

Liam Turner assisted with the production of a script for the batch processing of remote sensing data, provided GIS assistance, and provided comments on the paper.

[1] The Macquarie University policy for thesis by publication states that a thesis may include a relevant paper or papers that have been published, accepted, submitted or prepared for publication for which at least half of the research has been undertaken during enrolment. The papers should form a coherent and integrated body of work. The papers are one part of the thesis, rather than a separate component (or appendix) and may be single author or co-authored. The candidate must specify their contribution and the contribution of others to the preparation of the thesis or to individual parts of the thesis in relevant footnotes/endnotes. Where a paper has multiple authors, the candidate would usually be the principal author and evidence of this should appear in the appropriate manner for the discipline. MQ Policy: http://www.mq.edu.au/policy/docs/hdr_thesis/policy.html

The impact of fire on sand dune stability: surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016

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Abstract

This study aims to establish the common response of coastal dunes in Western Australia (WA) to fire within the medium-to-long term, in terms of ecological-geomorphic-climatic interactions to test the hypothesis that fire plays a role in coastal dune de-stabilisation. Fires are commonly suggested to have contributed to widespread dune reactivation in Australia and globally. This hypothesis is relatively untested. We used data from Landsat Thematic Mapper, Enhanced Thematic Mapper Plus, and Operational Land Imager to monitor changes in surface coverage on coastal sand dunes in south-west WA after fires. We analysed 30 fire scars from 1988 to 2016 in two Landsat scenes on the west and south coast of WA. Recovery ratios derived from the Normalised Difference Vegetation Index (NDVI) were used to monitor patterns in post-fire biomass and surface cover. We also used Maximum Likelihood Classification to monitor changes in bare sand area. Data are correlated with indices of burn severity, and meteorological data. Results suggest that recovery followed a strongly consistent pattern, and is characterised by rapid ground cover re-establishment within six to twelve months. Prior to this, some aeolian activity may have occurred but without substantial surface changes. Initial germination was followed by steady growth up to seven years, where NDVI typically neared pre-fire values. Some variation in early recovery occurred between the west and south coast, possibly owing to relative proportions of reseeding and resprouting plants. A log regression explained 75% of the recovery pattern (79% on the south coast). Precipitation had some ability to explain recovery up to nine months post-fire (r^2 = 0.29 to 0.54). No relationships were observed between estimates of burn severity and recovery. After nine months, the biggest cause of spatial variation in recovery was the pre-fire community composition and related seedbank or resprouting density. Image classification did not identify any new blowout features except where fires are not the primary cause. Results suggest that fires are not presently contributing to the de-stabilisation of coastal dunes in southwest WA.

Key words: Fires, Landsat, remote sensing, sand dunes, coastal, geomorphology

2.1 Introduction

Coastal dunes in Australia experience both stability and large areas of transgressive dune mobility (Hesp, 2013). The factors driving their bi-stability and, in particular, their activity have been speculated on but not comprehensively studied. Work in this field has included modelling and monitoring on Queensland's sand islands (e.g. Levin, 2011; Yizhaq et al., 2013; Levin et al., 2014), and the development of a conceptual model for coastal dune evolution (Hesp, 2013). In general, active coastal dunes in sub-tropical and temperate environments result from disturbance events at the coastline (often involving the de-stabilisation of the foredune, e.g. during a storm) or another geomorphic driver (e.g. littoral sediment supply) initiating massive inland transgression of sand (Hesp, 2002; Hesp and Martinez, 2007; Hesp, 2013). Active dunes may also result from the reactivation of previously stabilised dune deposits after a disturbance (Barchyn and Hugenholtz, 2013; Hesp, 2013).

Fire is often listed among disturbances that have the potential to cause de-stabilisation or at least deflation (Conacher, 1971; Martini, 1981; Christensen and Johnsen, 2001; Wiles et al., 2003; Lepczyk and Arbogast, 2005; Buynevich et al., 2007; Barchyn and Hugenholtz, 2013; Yizhaq et al., 2013; Ruz and Hesp, 2014). Specifically, fires are suggested to have played some role in widespread dune reactivation on the coast of Tasmania (Stockton, 1982), and in central Australia (Conacher, 1971), within the past two centuries. However, fires are not always recorded as the primary cause. For example, fires have been intentionally used to clear land for grazing (Stockton, 1982). There is also a lack of quantitative data accompanying these historical accounts. Other studies of linear dune activity in Tasmania over the past 30,000 years have linked dune activation near the modern northeast Tasmanian coast to altered fire regimes (possibly Aboriginal-related) (McIntosh et al., 2009; McIntosh et al., 2012). However, these links are only speculative and the same dunes appear mostly stable in the present climate (McIntosh et al., 2009; McIntosh et al., 2012). The flammability of heath vegetation on coastlines in Australia and other Mediterranean, temperate or sub-humid environments contributes to a strong presence of fires (Nieuwenhuis, 1987; Russell-Smith et al., 2007). Considering this regular disturbance, there has been surprisingly little attention given to establishing the role of fires in coastal geomorphology.

Though often speculated on, de-stabilisation (in particular, the initiation of blowout features) following fires has not been observed first-hand, and evidence is limited to buried charcoal layers in North America, Europe, and the Australian desert (Filion, 1984; 1987; Filion et al., 1991; Seppala, 1995; Kayhko et al., 1999; Mann et al., 2002; Carcaillet et al., 2006; Lomax et al., 2011; Matthews and Seppala, 2014). First-hand observations of post-fire aeolian activity have focused on enhanced localised saltation or suspension rates (e.g. Zobeck et al., 1989; Whicker et al., 2002; Vermeire et al., 2005; Sankey et al., 2009a; 2009b; Ravi et al., 2012; Stout, 2012) rather than dune activity or stability. Some authors (Barchyn and Hugenholtz, 2013) question whether dunes may be reactivated after fires, suggesting that it is dependent on vegetation type, fire severity, season and coincidence with drought conditions. Whilst fires occur along much of the Australian coast, evidence suggests this does not always initiate dune de-stabilisation. Rather, heath vegetation on eastern coastal dunes has been noted to recover after fire (Ward, 2006; Myerscough and Clarke, 2007). It is unclear whether there is a window of opportunity following fires, before regenerating plants reach effective coverage, during which wind-driven sand movement can produce substantial surface change, which in turn inhibits regeneration.

Fires on heath and scrub vegetation can kill mature plants, and also encourage massive germination owing to the adaptive reproductive traits of most native Australian species (Keeley, 1995; Burrows and Wardell-Johnson, 2003). Many species produce seeds which are protected from fire by fruit structures or hard coatings which subsequently open to allow post-fire germination (Keeley, 1995; Bell, 2001). However, seeds lying dormant in the seedbank which experience temperatures above a threshold (often around 150°C) will die, and resprouting plants also have a threshold burn frequency above which the resprouting process is impeded (Nieuwenhuis, 1987; Keeley, 1995; Bell, 2001). Additionally, post-fire heath regeneration can be affected by precipitation rates (Keeley, 1995; Benwell, 1998). Thus, short-to-medium term reduction of surface protection is related to burn intensity, burn severity, post-fire weather conditions, burn frequency and the species composition.

Coastal dunes in Western Australia (WA) have developed through the Quaternary, with Holocene deposits comprising a mix of stabilised dunes and large areas of currently bare transgressing sand (Overheu et al., 1993; Semeniuk and Semeniuk, 2011; Laliberté et al., 2012). Stabilising vegetation is typically extremely flammable and appropriate meteorological conditions for ignition occur regularly (Bradstock, 2010). Regular fires on dune areas provide a good opportunity to test the role of fire as a de-stabilising disturbance. The present day persistence of large bare transgressive dunes indicates that conditions are suitable for substantial aeolian activity. Therefore, given appropriate disturbance and sediment supply, dune de-stabilisation should be possible (Barchyn and Hugenholtz, 2013).

Our aim is to determine the common response of coastal dunes in WA to fire over time periods of 0 to 10+ years, in terms of climatic-geomorphic-ecological interactions to test the hypothesis that fire plays a role in coastal dune de-stabilisation. We used data from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) to monitor changes in surface coverage on coastal sand dunes in south-west Western Australia after fires. We analysed 30 fire scars from 1988 to 2007. This was primarily to monitor patterns in post-fire biomass and surface cover estimated from image-derived vegetation indices, and identify any occurrences of post-fire de-stabilisation using image classification. Data are correlated with indices of burn severity, as well as available meteorological data.

2.2 Materials and methods

2.2.1 Study area

We obtained data from two Landsat scenes over WA (Fig. 1). One scene covers part of the west coast of WA (near Jurien Bay, ~200 km north of Perth) within the Perth coastal plain (Brocx and Semeniuk, 2010). The second scene covers part of the south coast of WA. Both settings are sedimentary coastlines dominated by Quaternary limestone or aeolianite, with more recent beach and dune deposits (Brocx and Semeniuk, 2010; Brooke et al., 2014). The limestone was deposited as coastal dunes, including marine biogenic clasts and modified by pedogenesis, karstification and calcrete formation through the mid-to-late Quaternary (Brooke et al., 2014). Plains adjacent to the modern shoreline are covered with dunes deposited during times of high sea level (SL) (possibly reworked during low SL) (Semeniuk and Semeniuk, 2011; Brooke et al., 2014). The youngest deposits on the west coast, the Quindalup dunes, are associated with the Holocene transgression, though few absolute

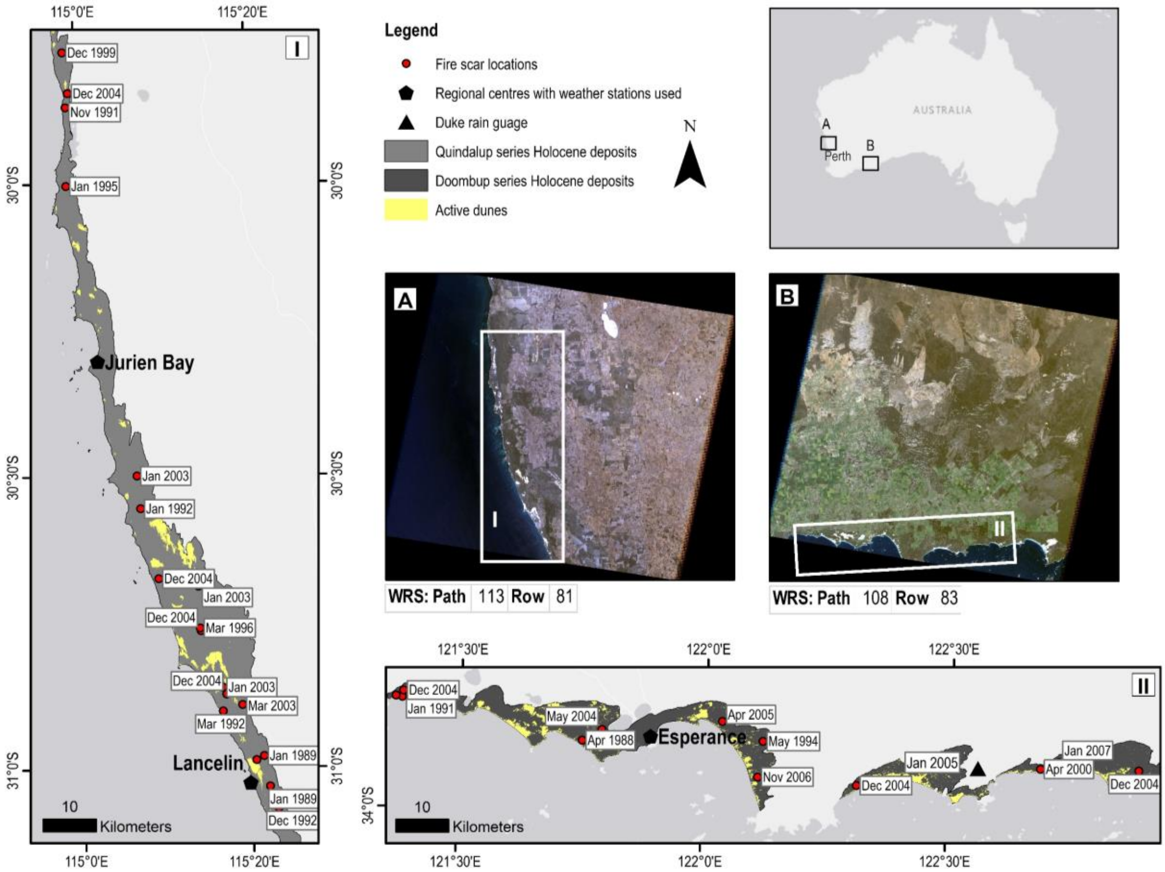

Figure 1: Regional setting showing locations of Landsat scenes on the west coast (A), and south coast (B). West (I) and south (II) coast settings with points indicating locations of fire scars (not indicating fire boundaries) within Holocene dune deposits (Quindalup and Doombup). Weather stations used for precipitation data in this study are marked as regional centres and one rural location (Duke) on the south coast.

ages exist (McArthur, 2004; Laliberté et al., 2012). These are described as complex nested parabolic dunes, composed of 20 to 80% carbonate material (McArthur, 2004; Wyrwoll et al., 2014). Due to their relatively young age, dissolution of carbonate is limited, as is calcrete formation, though some older Holocene dunes have soils with carbonate content reduced to ~20% (McArthur, 2004; Wyrwoll et al., 2014).

Dune deposits on the south coast follow a similar pattern to the west coast, though direct comparisons are tenuous due to the lack of age constraint (Overheu et al., 1993; McArthur, 2004). Dunefields near Esperance, WA, have developed in several phases (McArthur, 2004). Complex parabolic dunes similar in appearance to the Quindalup dunes, and seemingly of Holocene origin, are known as the Doombup series (Overheu et al., 1993). Older, more rounded dunes with lithified calcrete cores and a more east-west orientation are labelled the Tooregullup series (Overheu et al., 1993). Unlike the west coast, southern dunefields do not universally have a spatiotemporal gradient from young to old deposits moving inland. This gradient is most clear on west-facing shorelines. Elsewhere the systems have a more complex mix of phases overlying each other. On both coastlines there are extensive areas of active blowouts and transgressive dunes (Overheu et al., 1993; Semeniuk and Semeniuk, 2011; Laliberté et al., 2012). The geomorphic drivers of present activity have not been investigated.

The climate in both regions is Mediterranean with hot, dry summers and cool, wet winters (Laliberté et al., 2012; Hope et al., 2015). The west coast region experiences an average annual rainfall of 552 mm at Jurien Bay (1969-

2016), peaking in July, with the lowest rainfall occurring from December to February (Australian Bureau of Meteorology, http://www.bom.gov.au/climate/data/). The annual mean maximum temperature is 24.9ºC, peaking at 30.9ºC in February (Fig. 2a). The south coast region experiences an average annual rainfall of 617 mm at Esperance (1969-2016), peaking in July, with the lowest rainfall occurring from December to January. The annual mean maximum temperature is 21.9ºC, peaking at 26.2 ºC through January and February (Fig. 2a). This study falls in a period during which southwest WA has experienced a steady decline in precipitation since the 1970s, particularly during autumn and winter (Fig. 2b) (Beer, 2014; Delworth and Zeng, 2014). This is broadly associated with changes in the strength and position of the sub-tropical ridge (STR), and has been attributed to anthropogenic greenhouse gasses (Delworth and Zeng, 2014).

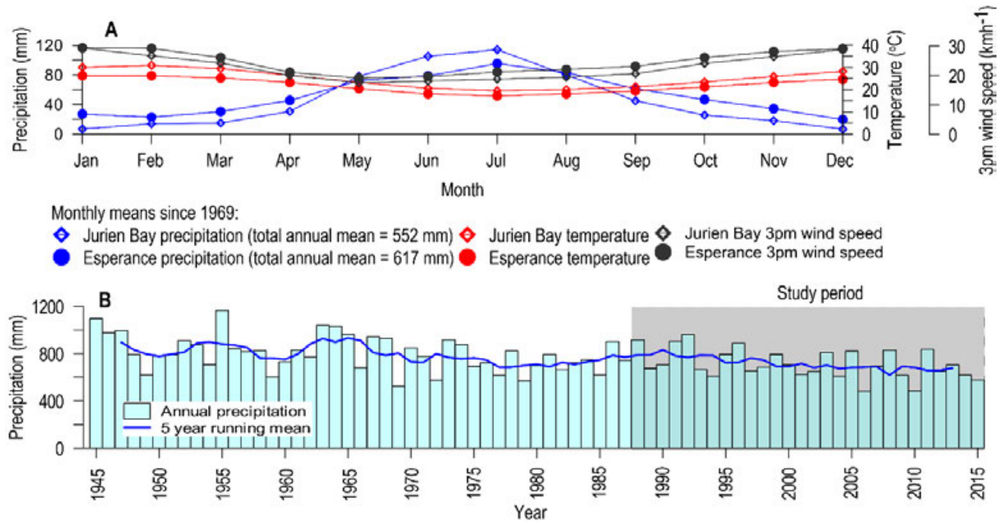

Figure 2: (A) Annual distribution of average monthly precipitation and temperature since 1969 for Jurien Bay and Esperance. Jurien Bay experiences relatively drier summers and wetter winters with lower overall precipitation than Esperance. Temperatures follow similar patterns for both regions with Jurien Bay seeing generally higher values (up to 31°C). (B) Annual precipitation recorded at Perth airport since 1945 shown with a 5 year running mean. The study period is marked in the most recent decades after a steady decline in rainfall. Source: http://www.bom.gov.au/climate/data/

Vegetation on Quindalup dune systems is typically a mixed tall and low sclerophyll shrubland with species of *Acacia*, *Melaleuca*, *Allocasuarina*, *Banksia*, and other genera of Proteaceae and Myrtaceae (Beard et al., 2013). On the Doombup dunes, vegetation composition is open scrub dominated by species of *Acacia*, *Melaleuca* and *Leucopogon* (Overheu et al., 1993; Beard et al., 2013). Heath vegetation in south-west Western Australia has evolved through recurring fires and typically possesses traits suited to post-fire regeneration (Keeley, 1995; Gosper et al., 2010). Historically, Aborigines have had a strong influence on fire regimes in WA (Hassell and Dodson, 2003). Fire intervals of 30 to 100+ years have been inferred from lake sediment charcoal deposits in areas with no Aboriginal inhabitants (Hassell and Dodson, 2003). Where Aboriginal burning occurred, fires were typically more frequent, depending on population density and the practices of individual groups (Hassell and Dodson, 2003). Fire intervals have been altered further under European management (Gosper et al., 2010; Lambrook, 2015). No study has comprehensively described present fire regimes on coastal dune heaths in WA. They are considered highly variable and related to the distribution of anthropogenic fire incidents (Bradstock, 2010; Lambrook, 2015). For natural fires, the coincidence of typical dry summers with lightning from northern cyclonic activity brings extreme fire risk every ~5 years for dry sclerophyll shrub (Bradstock, 2010). Actual ignition intervals apparently vary from 5 to 25 years (Bradstock, 2010).

2.2.2 Methods

Dune areas

We first defined the spatial extent of our analysis. To isolate the protective role of vegetation and reduce the influence of surface cohesion from cemented calcareous substrates, the study was confined to Holocene dune development (Laliberté et al., 2012). Though little work has been done to map or obtain absolute dates for dunes in WA, it is accepted that Holocene deposits (Quindalup and Doombup) have a complex parabolic form, and are distinguishable from Pleistocene deposits with more rounded surfaces, different vegetation, and, at times, a different orientation (Overheu et al., 1993; McArthur, 2004; Beard et al., 2013). We mapped the Holocene extents over base map imagery in ArcMap (Fig. 1). Some interdunes may have calcrete from older sand sheets near the surface, while the stabilised crests more often contain substantial volumes of unconsolidated sediment (Semeniuk and Semeniuk, 2011). Without high-resolution Digital Elevation Models (DEM), this analysis did not differentiate between dune crest and interdune areas.

Spectral indices

Burnt areas can be identified in Landsat TM, ETM+ and OLI data by a sharp drop in Near Infrared (NIR) values when compared to surrounding vegetated areas (Fig. 4a; b; c) (Hugenholtz et al., 2012; Lu et al., 2015). In this environment burnt areas also stand out in true colour imagery (Fig. 4a) (Lambrook, 2015). Image selection was constrained to those with <40% cloud cover, and where clouds were absent along the coastline. Images were processed and analysed in ENVI 5.3 and IDL 8.5 software. Time-series analysis began with images immediately prior to fires (see Appendix 1 for the list of images processed). Images were radiometrically and atmospherically corrected using the Quick Atmospheric Correction (QUAC) code (Bernstein et al., 2012). The QUAC algorithm can produce an error of ±15% when compared to the available Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module (Bernstein et al., 2012). QUAC was chosen for batch processing capabilities due to the large number of images (150+) (see Appendix 1). It was also deemed acceptable because the difference in reflectance between bare sand and green coastal vegetation is typically >15%. A variety of spectral indices were then used to map fire areas and assess fire-related biomass loss and subsequent recovery (Fig. 3). The Normalised Difference Vegetation Index (NDVI) has been widely used to track post-fire recovery in heathlands and elsewhere (Henry and Hope, 1998; Díaz-Delgado et al., 2002; Díaz-Delgado et al., 2003; Hope et al., 2007; Hugenholtz et al., 2012; Levin et al., 2012; Ravi et al., 2012; Lu et al., 2015). The absorption of red visible light and reflection of NIR by plant cells enables the estimation of biomass in a pixel (Table 1) (Tucker, 1979). We did not collect reference data for estimating actual ground cover from NDVI, rather, we used NDVI as a proxy for relative biomass and surface coverage (Díaz-Delgado et al., 2002).

The post-fire drop in NDVI is shown by the difference NDVI (dNDVI), calculated between pre- and post-fire NDVI images (Table 1) (Díaz-Delgado et al., 2002; Díaz-Delgado et al., 2003; Morgan et al., 2014). We mapped fire scars using the contrast provided by dNDVI (Fig. 4c). Fire scars were chosen for analysis where; imagery could be used to place the timing confidently within one month, and; there had been adequate time since the fire to properly assess recovery and response (i.e. all fires up until ~2007, allowing for a 10 year recovery period (Myerscough and Clarke, 2007; Meng et al., 2014). On some occasions, images taken around the time of burning were obstructed by clouds. Consequently, the cloud-free images chosen for dNDVI were too far apart, generating noise from natural changes in NDVI signal in surrounding vegetation. For these fires, the Normalised Burn Ratio (NBR), which utilises variation in the Shortwave Infrared (SWIR) wavelengths, was used to generate a clearer fire-scar image (Table 1). Most study areas were covered with natural vegetation. However, the NBR was also used where heath vegetation had been cleared and NDVI values on dry grasslands were already low prior to burning. Some fires near Wedge Island (north of Lancelin) are occasionally ignited by military activities. In this study, we were not able distinguish between natural and unnatural fires. Similarly, despite the importance of fire frequency in ecological responses to fire (Keeley et al., 2011), difficulty in establishing localised fire intervals led to its exclusion as a variable.

Table 1: Spectral indices used

Index	Equation	Reference
NDVI	(NIR – R)/(NIR + R)	(Tucker, 1979)
SAVI	(NIR – R)/(NIR + R + 0.5) + 1.5	(Huete, 1988)
dNDVI	$NDVI_{PRE\text{-}FIRE} – NDVI_{POST\text{-}FIRE}$	(Díaz-Delgado et al., 2003)
NBR	(NIR - SWIR2)/(NIR + SWIR2)	(Key and Benson, 1999)

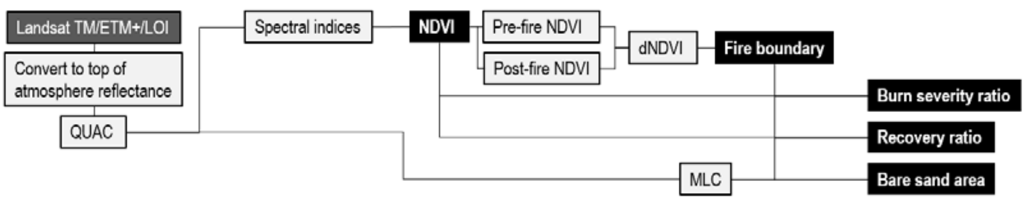

Figure 3: Data flow diagram showing main techniques used on Landsat data

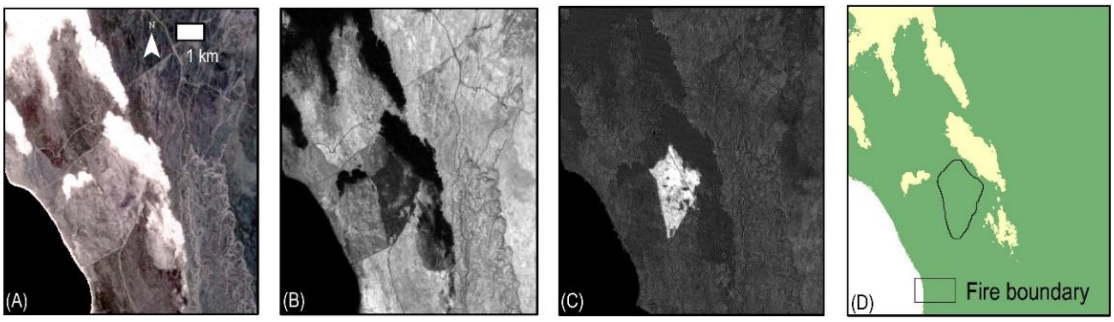

Figure 4: (A) Natural colour Landsat TM. (B) Normalised Difference Vegetation Index (NDVI); (C) Difference NDVI (dNDVI) showing fire scar; (D) Supervised Maximum Likelihood Classification (MLC) showing bare sand and vegetation with the mapped fire boundary. In all images the Indian Ocean (west) has been masked out.

Once fire scars had been mapped in each region, three equally sized regions within each scene (west coast: 15.2 ha, south coast: 32.6 ha) of vegetated dune surface which were not burnt in this period were selected as control sites for monitoring. These sites covered a range of environments, from undulating dune topography with sparser vegetation, to flatter interdunes with denser coverage. Spectral values varied spatially between sites, providing a good range for comparison with burn scars which also cover a range of dune surfaces. Temporal trends at each site were consistent with strong relationships (r^2 = 0.49-0.87) (see Appendix 3 for locations and relationships between reference sites).

NDVI values can be affected by soil properties, shadows of growing vegetation, seasonal changes in phenology, and signal saturation in dense canopies (Jackson and Huete, 1991; Carlson and Ripley, 1997; Díaz-Delgado et al., 2002; Hugenholtz et al., 2012). A Soil Adjusted Vegetation Index (SAVI) was trialled in case of soil influence on the spectral signal where ground cover is sparser (Table. 1) (Hugenholtz et al., 2012). We found SAVI to correlate strongly with NDVI values for all sites at all times (r^2 = 0.99) (see Appendix 2). This is likely because there is denser vegetation coverage than in the arid regions where SAVI is useful (Levin et al., 2006; Levin et al., 2008). The canopy scattering in NIR wavelengths, which enhances the soil signal, occurs least with dense coverage (e.g. healthy coastal heath), and nearly bare surfaces (e.g. recently burnt) (Huete, 1988). Furthermore, coastal dunes provide consistent light soil signals, appropriate for analyses of relative biomass signals. We therefore show results for NDVI only. Additionally, coastal heaths in WA do not have large volumes of understorey plant mass sheltered by canopies, which dampens the adverse effect of NDVI saturation. Thus, temperate and sub-humid coastal dunes are ideal sites for using NDVI.

The occasional localised distortion of pixel value placement (up to two pixels) within Landsat data caused bare dune pixels straddling the fire boundary to erroneously move into and out of fire polygons. This error is distinct from the natural migration of dunes into our study areas through time. To account for this distortion, mean NDVI outputs (and classification figures, discussed below) were taken for entire fire scars except for a four pixel (120 m) edge buffer. We took the mean NDVI from fire scars and from all control sites in a region. Following Diaz-Delgado et al. (2002; 2003), we derived a quotient between the mean NDVI within a given burnt area ($MeanNDVI_{BURNT}$) and control values ($MeanNDVI_{REFERENCE}$) (termed QNDVI):

$$QNDVI = MeanNDVI_{BURNT}/MeanNDVI_{REFERENCE} \quad (1)$$

This within-image ratio between biomass in burnt and healthy patches of vegetation normalises for fluctuations in plant phenology, climate (e.g. drought), and image illumination, which otherwise affect NDVI values (Díaz-Delgado et al., 2002; Díaz-Delgado et al., 2003). QNDVI should also normalise for small errors from the QUAC algorithm. If the study site shared identical spectral properties to the control areas, then it is assumed to be regenerated when post-fire QNDVI approaches one (Lu et al., 2015), otherwise regeneration is achieved when QNDVI nears pre-fire values. However, effective surface protection may be restored long before full regeneration

(Levin et al., 2012). After deriving QNDVI, we used the following equation [adapted from Levin et al. (2012)] to estimate recovery in terms of the initial loss in biomass:

$$RR = \frac{(QNDVI_T - QNDVI_{POSTFIRE})}{(QNDVI_{PREFIRE} - QNDVI_{POSTFIRE})} \quad (2)$$

where Recovery Ratio (RR) is the ratio between the recovery of QNDVI from immediately post-fire ($QNDVI_{POSTFIRE}$) to the time in question ($QNDVI_T$), and the QNDVI signal that was initially lost from pre- ($QNDVI_{PREFIRE}$) to post-fire.

To estimate burn severity, we used a variation of dNDVI. Diaz-Delgado (2003) successfully correlated dNDVI with on-ground assessments of fire damage ($r^2 \approx 0.9$). Elsewhere dNDVI has matched other burn indices (e.g. differenced NBR) for effectiveness, particularly within shrubland and forest (Fox et al., 2008; Morgan et al., 2014). Here, we estimate burn severity using the ratio between the QNDVI signal lost (i.e. difference QNDVI), and pre-fire values ($QNDVI_{PREFIRE}$), termed the Burn Severity Ratio (BSR):

$$BSR = \frac{(QNDVI_{PREFIRE} - QNDVI_{POSTFIRE})}{QNDVI_{PREFIRE}} \quad (3)$$

We note that using remote sensing to estimate burn severity is subject to error where a cloud-free image is not available soon after the fire. This should only allow extreme cases should this allow significant recovery in between (e.g. 2+ months delay). Furthermore, variations of dNDVI will primarily show loss in terms of chlorophyll and green biomass (Díaz-Delgado et al., 2003), while other forms of damage to plants such as the disintegration of woody structures when branches and trunks are burnt down might not be reflected.

Precipitation

To aid with the interpretation of remote sensing results, precipitation data was obtained from four local Bureau of Meteorology stations shown in Figure 1. This data was used to investigate the influence of early precipitation on vegetation regrowth after fires (Keeley, 1995; Benwell, 1998). For each fire we calculated the cumulative precipitation over three months, beginning at the end of the month within which the fire occurred. Values were taken from the nearest source for each fire. This variable, along with BSR values, were related to recovery ratios to investigate possible influences on short to medium-term recovery.

Bare sand monitoring

In order to identify major landscape changes related to fires, following Shalaby (2007), Berberoglu et al. (2004) and Janke (2002) we used supervised Maximum Likelihood Classification (MLC) to identify and monitor 30 m pixels classed as bare sand. This was completed on yearly images in both scenes from 1988 to 2016. Two classes ('bare sand' and 'vegetated') were chosen, emphasising identification of bare sand (distinguished by a high albedo) amidst vegetated dunes. Multi-temporal classification over 28 years on such a spatial scale provided several challenges. Firstly, training data needed to be visually chosen without field data from within

Landsat images and with the aid of higher resolution ArcMap base imagery. Secondly, classified images needed to be temporally comparable. To this end, all images in a scene were trained with the same polygons. Training data were extracted from individual images within these polygons. We chose training areas for vegetation where there had not apparently been a fire within the study period to avoid substantial changes in the spectral properties of training data. This theoretically allowed the MLC to appropriately classify burnt areas as 'bare' or 'not bare'. Similarly, we ensured that bare sand training areas were consistently bare and unaffected by dune migration.

It is best practice to check classification accuracy with ground-truthing (Janke, 2002; Shalaby and Tateishi, 2007; Berberoglu and Akin, 2009). Since ground truth data were not available across both scenes for all 28 years, validation required high resolution imagery. We obtained one Red Green Blue (RGB) aerial photograph with 0.5 m spatial resolution captured over coastal dunes west of Esperance, WA, on 24 March 2013 from the Western Australian Land Information Authority. This was classified into bare sand and vegetation, over which we systematically generated 4507 control points in a grid with 200 m spacing. These points were matched with the overlapping classification of a Landsat 8 image captured on 22 June 2013 to produce an error matrix. These validation results are used as a general indicator of classification accuracy. We acknowledge the limitations without valid ground truthing across all images. We did, however, visually inspect classifications over original images to check bare sand was being classified effectively and investigate causes of variation. Here, numerical results are presented, but are treated with caution.

2.3 Results

2.3.1 Vegetation monitoring

For all 30 fires assessed between 1988 and 2007 there is a scatter of QNDVI values pre-fire (~0.8 to 1.1), reflecting the spatial variability of the natural unburnt vegetation cover. This pre-fire range may influence the similar, though slightly narrower, scatter of immediately post-fire QNDVI (Fig. 5a). The post-fire range is narrowest immediately after fires (~0.4 to 0.6), with no values dropping below 0.4 (Fig. 5a). Mean values across all fires show a consistently steep rise in the first six months, with a slightly higher mean value on the south coast at 4 to 6 months (Fig. 5a). This steep rise continues for the west coast region up to 0.8 from 7 to 12 months (Fig. 5a). Recovery rates then temporarily plateau until 24 months (Fig. 5a). On the south coast, overall mean QNDVI temporarily ceases to increase after six months, hovering between 0.6 and 0.7, before resuming a steady recovery rate after 18 months (Fig. 5a). In both regions, the initial steep rise in QNDVI is interpreted as returning NDVI signal from resprouting plants. Beyond 18 months, points are horizontally clustered because we chose to analyse images at approximately 12 month intervals (Fig. 5a). Between 18 and 80 months there is a steady increase in QNDVI, reaching close to pre-fire values at between 60 and 80 months (Fig. 5a). The west coast region reaches a peak mean value of 0.97 near 60 months post-fire, but stagnates and does not reach the mean pre-fire value within the study period (Fig. 5a). The south coast takes up to 80 months to plateau at 0.94, which is above typical pre-fire values (0.93). The south coast then remains around this value for the duration of the

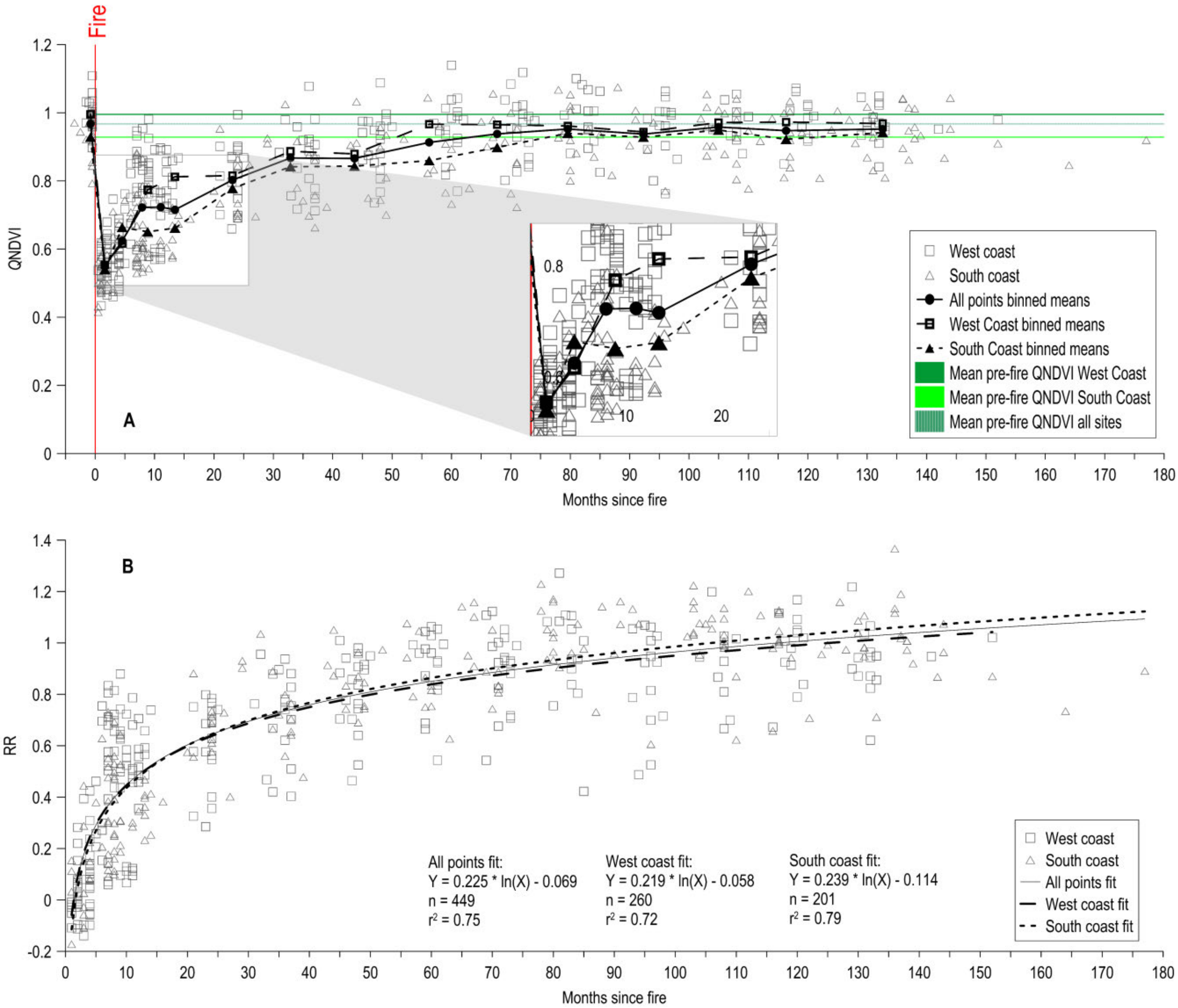

Figure 5: NDVI monitoring. (A) Measurements of QNDVI across all 30 fires plotted with complete months before and after fire with mean lines shown for all sites and individual regions. Means are taken from binned time periods ranging from 3 to 12 months in size. Magnified section highlights the separate behaviour of the study regions from 6 to 24 months. (B) All values of Recovery Ratio (RR) plotted with time since fire. Regression shows a logarithmic pattern with reasonable correlation.

study (Fig. 5a). The scatter of points shows some sites reaching above the average pre-fire QNDVI across all sites, as well as some points tracking well below the mean, possibly in areas of comparatively sparse or dry native vegetation (Fig. 5a). The vertical range of points is largest between 10 and 70 months, before becoming a narrower spread of values after 80 months (Fig. 5a).

When RR is generated by normalising QNDVI with the initial loss of QNDVI, there is a very similar pattern (Fig. 5b). A log regression can be used to explain 75% of the recovery pattern (79% on the south coast) (Fig. 5b). The recovery pattern has good consistency, but the vertical spread in RR is also likely influenced by various other factors (e.g. precipitation, species distribution). Note that within 10 months some points regain close to 90% of the lost QNDVI signal (Fig. 5b). After 30 months many points from both regions show NDVI signal recovery greater than the initial loss (Fig. 5b). In this case, a dense coverage of re-growth should be more photosynthetically active than fully grown shrubs, thus giving a stronger NDVI signal (Bond, 2000). Between 80

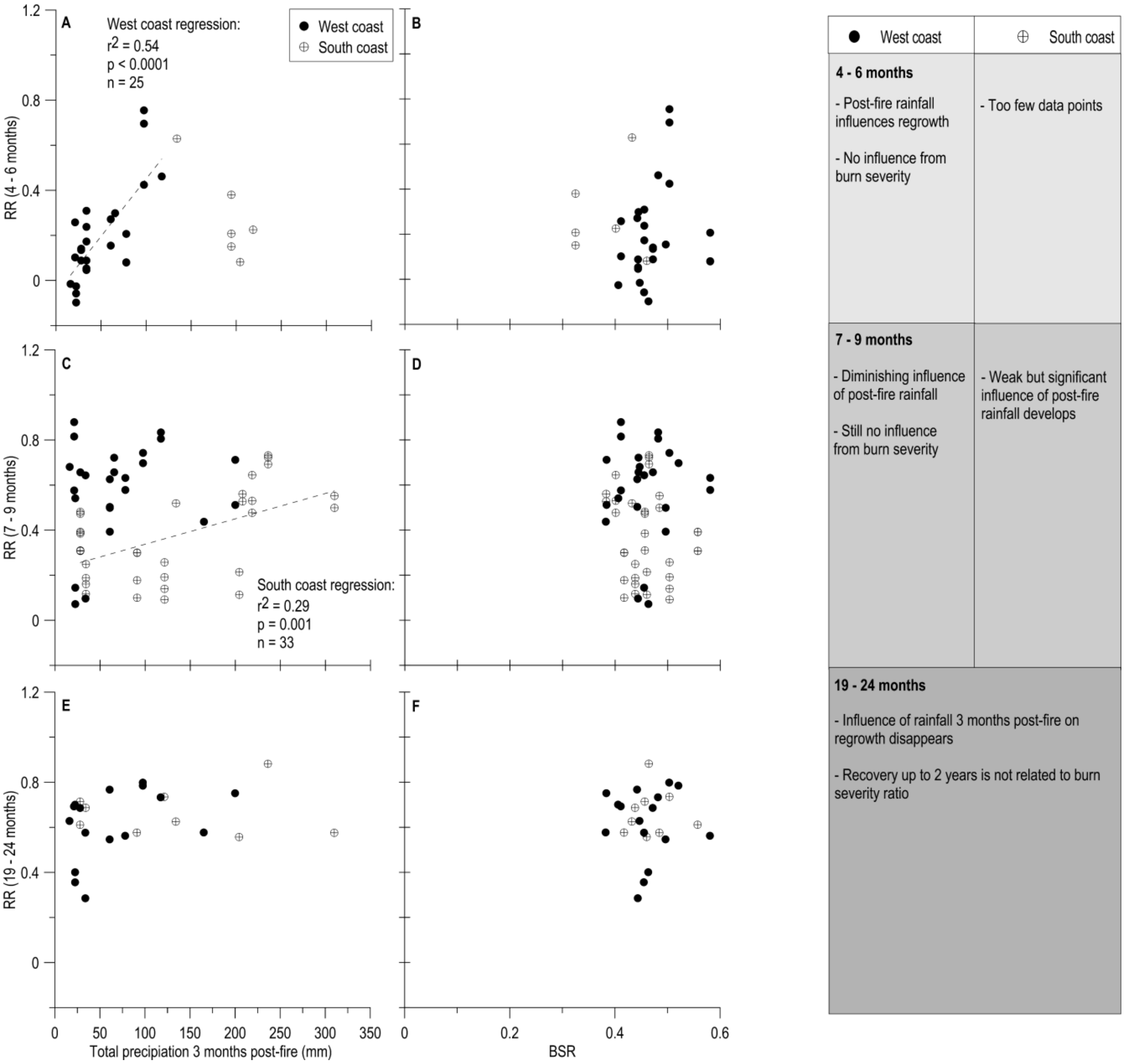

Figure 6: Cross plots exploring the relationships of early post-fire rainfall in the initial 3 months post fire (A, C, & E) and burn severity ratio (BSR) (B, D, & F) with recovery ratios (RR) within three time periods: 4-6 months (A & B), 7-9 months (C & D), and 19-24 months (E & F). Regression analysis is shown only for individual regions, and only in time periods where a significant relationship was found. Note that plots show points from binned time periods (in order to increase sample size), and therefore distributions possibly reflect a temporal change as well as influence from variables.

and 100 months, several values from the west coast appear to decline before increasing once more (Fig. 5b). It is unclear whether this is related to the fire incident.

Precipitation has some ability to explain recovery up to nine months, while no relationships can be seen with estimates of burn severity (Fig. 6). For RR taken from four to six months on the west coast, rainfall in the immediate post-fire period was found to have a moderate (r^2 = 0.54) and significant ($p < 0.0001$) correlation (Fig. 6a). We acknowledge the danger in cross plotting binned data with a temporal range (as there is the possibly this would influence values). Nevertheless, areas which experienced higher initial post-fire precipitation rates saw higher recovery in the first six months. Note that higher south coast rainfall (when compared to the west coast) did not result in higher RR, though we have too few points to draw conclusions about a relationship between precipitation and RR (Fig. 6a). At seven to nine months, the correlation on the west coast between post-fire precipitation and RR diminishes (Fig. 6c). There is, however, a weak (r^2 = 0.29) but significant (p = 0.001) correlation that develops for the south coast region between precipitation and RR (Fig. 6c). This development appears to correspond with the lower mean QNDVI values during this period on the south coast (Fig. 5a). At no point does BSR correlate with recovery, and, after two years, RR is neither explained by BSR, nor by post-fire precipitation (Fig. 6e, f).

2.3.2 Classification and surface change

The key statistics identified in the classification validation process are the relatively strong Kappa Coefficient (0.77), and the user accuracy for bare sand of 89.41% (Table 2). With this we can expect that for the validated image, ~90% of pixels classified as bare sand are correct. This number does not apply to all classified images. However, we can speculate with reasonable confidence that the MLC, which used the same training polygons for each image, could reliably distinguish between vegetation and bare ground, which have strongly contrasting spectral properties. Visual inspections confirmed a general reliability of bare sand identification.

Table 2: Validation results for the classified image captured on 24/03/2013

Class	Omission (%)	Commission (%)	Producer accuracy (%)	User accuracy (%)
Vegetated	2.99	7.68	97.01	92.32
Bare	24.25	10.59	75.75	89.41
Overall Accuracy = (4134/4508) 91.7% Kappa Coefficient = 0.77				

The image used for validation did not cover large areas of sparse or low vegetation cover which, though not common, are seen in some locations, often immediately after fires. Therefore, while we are confident that the MLC using the chosen training polygons could distinguish between vegetation and bare ground, its ability to classify partially vegetated surfaces is relatively untested. This is especially pertinent in the period immediately post-fire. Classifications of images taken shortly after fires sometimes resulted in large areas of bare sand within the burn scar (Fig. 7k). While this result seems appropriate and is consistent with other observations of scarce post-fire ground cover (e.g. Sankey et al., 2009a; Levin et al., 2012), its occurrence is sporadic, and depends on the nature of vegetation within the training areas for any given image. In months where training vegetation was especially green, burnt pixels aligned more closely with the spectral properties of bare sand (Fig. 7k). The occasional shadow effect of steep slip-faces on bare dunes gave patches of shaded bare sand similar spectral properties to those of freshly burnt surfaces. When this did not occur, bare ground on burnt surfaces may be shaded by remnant frames of trees and shrubs, providing contrast to highly reflective dunes and misclassifying burnt surfaces as vegetated. Given the inconsistency, we provide numerical results for classification only after at least one year has passed (Fig. 8). This does not eradicate the error, but theoretically highlights only those pixels which persist in the state of partial or ambiguous coverage well-beyond the typical period of rapid biomass recovery shown in Figure 5.

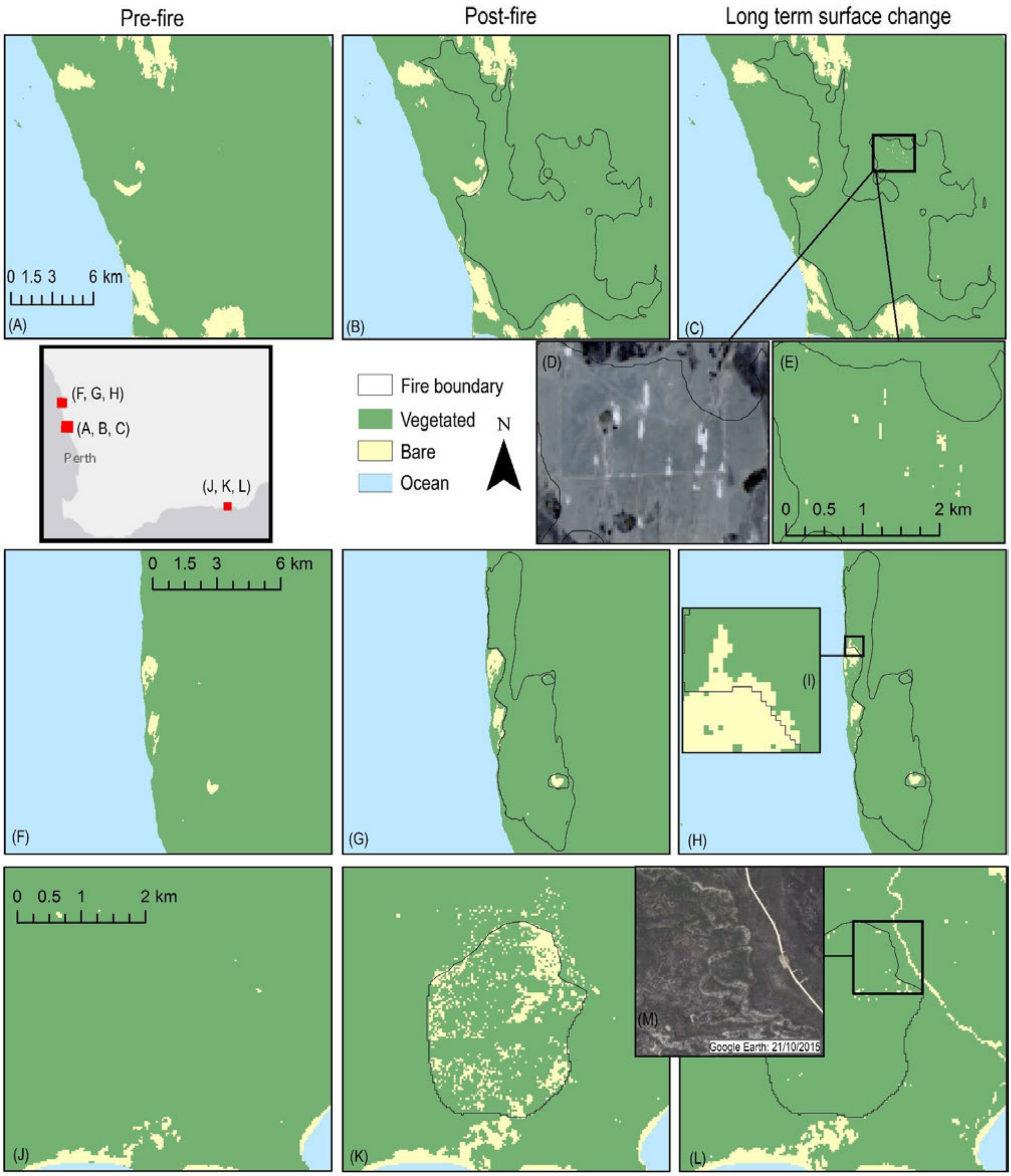

Figure 7: Case studies of image classification showing results of pre-fire (left), post-fire (middle), and several years on (right). (A-E) Fire near Wedge Island, WA (north of Lancelin), December 2004. (A) December 2004; (B) November 2005; (C) December 2015; (D) true colour image showing localised blowouts on cleared land; (E) blowouts shown with image classification. (F-I) Fire near Leeman, WA (north of Jurien Bay), December 1999. (F) October 1998; (G) December 1999; (H) December 2015; (I) Inset showing migrating dunes encroaching into study area. (J-M) Fire near Howick, WA (east of Esperance), January 2007. (J) December 2006; (K) August 2007; (L) May 2016; (M) Google Earth image showing sandy road with high albedo, and areas recovered since the fire with no blowouts but sparse vegetation on dune crests at times being classified as bare ground. See Figure 1 for fire locations.

At times, sandy roads within the fire boundaries would fluctuate in albedo, perhaps due to clearing and maintenance (Fig. 7l). This could cause a temporary spike in the number of bare pixels classified within a study area. The long term encroachment of nearby migrating (previously-active) dunes into study areas also incidentally affected bare sand pixel counts (Fig. 7i). Two of the case studies shown in Figure 7 show a long term persistence in bare sand pixels which appear to be post-fire phenomena. Rather than active dunes, bare-classified pixels nine years after a fire near Howick on the south coast (east of Esperance) are seen in higher resolution imagery to be areas of sparse vegetation cover on dune crests (still relatively stable) (Fig 7l, m). Other small bare patches resulted from falling water tables in once-swampy interdunes (Fig 7l, m). On the west coast near Wedge Island (north of Lancelin), emergent bare pixels are confirmed as small blowouts (~60 m wide) (Fig. 7c, d, e). These occur on dune crests within cleared land, presumably agricultural (Fig. 7d). Closer inspection of pre-fire imagery shows the blowouts are not a post-fire feature, but were too small prior to the fire for the 30 m classification to identify. We do not rule out fire as a disturbance which could have enhanced their development, but their initiation appears more related to vehicle pathways.

Plots of bare sand pixel counts within all fire boundaries (relative to pre-fire counts) reveal several increases of up to 300 pixels, sometimes temporary, elsewhere persisting (Fig. 8). A spike seen on the west coast (fire: Wedge Island, December 2004) at five years post-fire shows the temporary inclusion of a sandy road into bare pixel counts (Fig. 8a). More persistent increases on the west coast are due to migrating dune encroachment

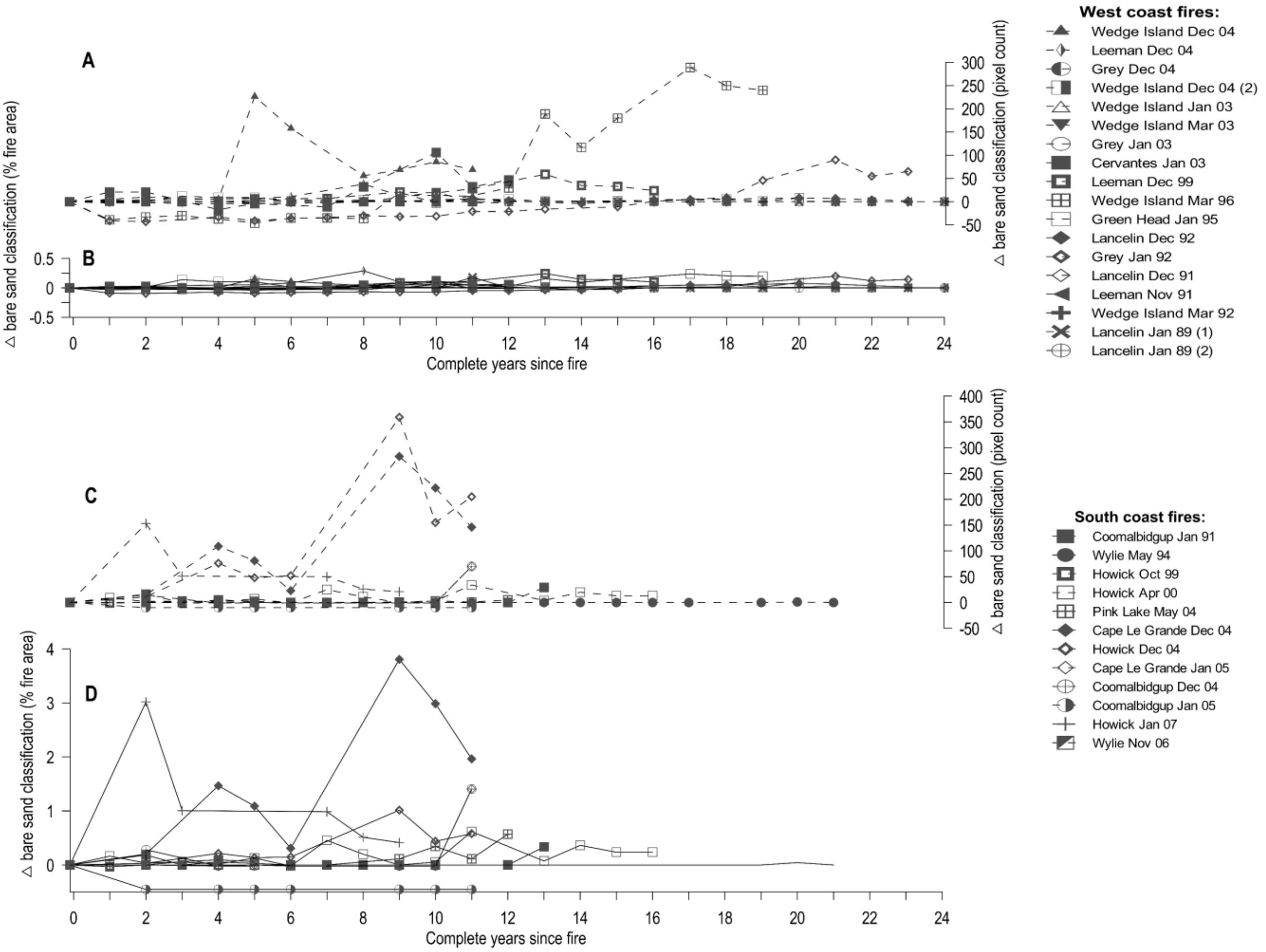

Figure 8: Time series plots of the change in bare sand classification (pixel counts and % of total burnt area) relative to pre-fire values. After point 0, plots begin at one full year post-fire. (A) West coast change in pixel count; (B) west coast change in % burnt area; (C) south coast change in pixel count; (D) south coast change in % burnt area.

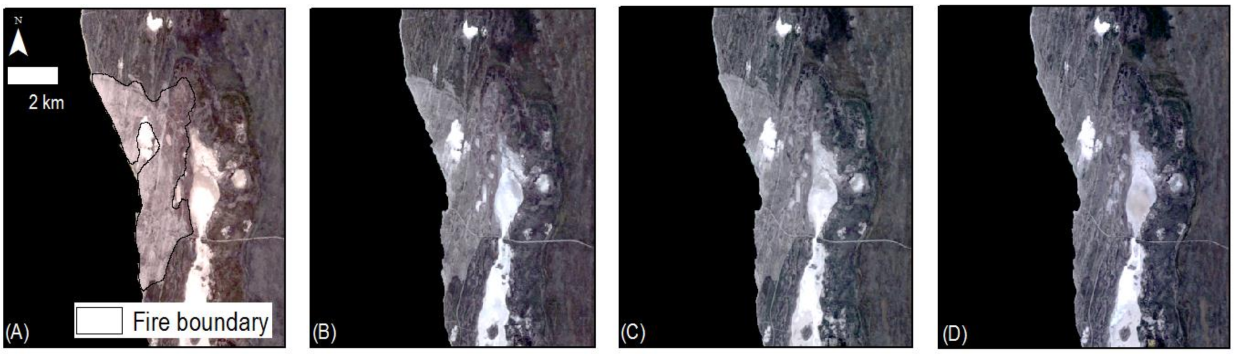

Figure 9: Sequence of natural colour Landsat TM images showing dunes burnt in December 2004 near Leeman, WA. Time-series shows vegetation recovery with no blowout development. (A) 8 January 2005 (~1 month post-fire); (B) 27 January 2006 (1 year post-fire); (C) 14 January 2007 (2 years post-fire); (D) 9 January 2011 (7 years post-fire). In all images the Indian Ocean (west) has been masked out.

(e.g. Wedge Island, March 1996, and Grey, January 1992) and clearing for development (e.g. Lancelin, January 2003) (Fig. 8a). When these increases are plotted in terms of percentage of total fire, their significance diminishes, as all changes are <0.5% (Fig. 8b). On the south coast, several sites show higher percentage increases in bare sand (<4%) (Fig. 8d). These fires occurred east of Esperance near Cape Le Grande and Howick. In these locations, vegetation coverage can be sparse on dune crests, on calcrete interdunes with low nutrients, or on small bedrock outcrops where the dune sheet is only thin. Due to a lack of available unburnt sparse vegetation, training polygons on the south coast were drawn over regions of relatively dense coverage. Therefore, ambiguous partially vegetated surfaces are widespread in these areas. In every case of bare sand increase, further examination revealed no genuine blowout development after or related to a specific fire incident. By contrast, the vast majority of pixels returned to a vegetated state and remained vegetated (Fig. 8; 9). Figure 9 shows an example of this typical response after a fire in December 2004 near Leeman, WA (north of Jurien Bay). An image captured on 8 January 2005 shows a pale fire scar with a high reflectance from an almost bare surface (Fig. 9a). After one and two years, the fire scar remains distinctive but faded due to re-growth (Fig. 9b; c). By seven years post-fire, the burnt area is not easily distinguishable from surrounding dunes and no blowouts have formed (Fig. 9d).

2.4 Discussion

2.4.1 Patterns of vegetation recovery

The general trend seen here is the strong consistency of vegetation re-growth in the coastal dune environment, with slight variations between regions and individual sites (Fig. 5a). The scatter of QNDVI values both pre- and post-fire is likely related to spatial variations in vegetation structure compared to reference sites [e.g. dominant species will give different NDVI signals according to changes in leaf structure (Hesp, 1991)], or because areas are not fully recovered after previous fires (Fig. 5a). The overall recovery pattern and inter-site variation strongly resembles other post-fire NDVI monitoring results from Californian heathlands with nearly identical rainfall patterns (Hope et al., 2007). Importantly, in WA the strong pattern of recovery (apparently unimpeded by substantial surface erosion) occurs despite the apparent vulnerability of dune environments to disturbance, in a setting where active dunes are common. Particularly notable is the rapid recovery and associated surface stabilisation within six months after fires (Fig. 5a). The steady rise of QNDVI beyond 18 months observed here may reflect the general re-establishment of shrub species growing up from saplings, after the initial rapid widespread germination (Fig. 5a). The plateauing of NDVI at 60 to 80 months is unlikely to represent a full recovery of the vegetation community (Myerscough and Clarke, 2007). Rather, it records photosynthetic ground cover reaching a similar density to pre-fire conditions. While fire temporarily produces conditions likely to encourage aeolian activity, fires in Australian coastal heath vegetation simultaneously encourage the rapid return of effective ground cover (in the form of seedlings) via multiple mechanisms (e.g. reproductive traits, access to light, abundant nutrients, and reduced predators) (Keeley, 1995).

Regeneration in West Australian heath occurs either via re-sprouting from sub-surface epicormic buds (or sometimes within branches), or by seed re-establishment, or both (Keeley, 1995; Bell, 2001). Seed re-establishment can be from seeds within the seedbank whose hard casing has been cracked by the heat of the fire, or seeds released from cone/fruit structures which open after experiencing high-temperatures, known as serotiny (Keeley, 1995). Reseeders in Western Australian coastal heath have higher germination rates, earlier post-fire recruitment, faster growth rates than resprouters (Bell, 2001). Their seeds also have a higher tolerance for temperature (Bell, 2001). However, higher shoot:root ratios and lower energy stored in root systems mean that survival of the first summer drought is uncertain (Bell, 2001). Studies have shown a higher proportion of reseeding plants (~48%) on southern coastal regions than the west coast (~25%) (Bell and Loneragan, 1985; Bell, 2001; Hassell, 2001). While site-specific species compositions likely exist, such figures could explain why the south coast gives stronger NDVI signals up to six months (with higher seedling recruitment), followed by a stagnation or subtle decline (perhaps from low seedling survival rates) (Fig 5a). In either case, adaptations of heath vegetation are suited to a rapid recovery of effective ground cover.

2.4.2 Explaining recovery variability

One key dynamic of the coastal environment is the availability of rainfall for recovery. In an arid environment with different species distributions and lower precipitation rates, Levin et al. (2012) observed considerably lower post-fire vegetation cover after five years (44.3%), and only saw comparable levels of cover after ten years (84.3%). We infer from our data that the first six months is a critical time period for the re-establishment of effective ground cover on coastal dunes of the west coast of WA (Fig. 6a), even with a possible fire-induced water repellency (Ravi et al., 2006). An important relationship is seen on the west coast between cumulative precipitation in the first three months following a fire, and RR estimated from four to six months post-fire. Thus, areas which experience lower post-fire precipitation are likely more susceptible to early post-fire erosion. Despite the generally higher recovery on the south coast up to six months, recovery can stagnate beyond this point (Fig 5a). Figure 6c suggests this stagnation (RR <0.4 from seven to nine months) is partly influenced by early precipitation rates. This may be related to the lesser ability of the more dominant reseeders to survive the onset of higher temperatures and decreasing rainfall during the following spring and/or summer (Fig. 2a) (Bell, 2001). However, despite the influence of rain on early recovery, the diminishing relationship with time suggests once a site eventually receives the necessary precipitation for mass-germination, ground cover is inevitably re-established (Keeley, 1995; Benwell, 1998).

Unlike early precipitation, BSR was found to have poor explanatory power for recovery in all time periods (Fig. 6). Dunes may not have experienced fire intensities sufficient to impede recovery rates during our study period. Alternatively, BSR may not reflect the mechanisms likely to influence post-fire ecological-geomorphic interactions. In particular, the key to plant re-growth success is likely the temperatures experienced during fires (and sometimes smoke) (Keeley, 1995; Bell, 2001; Díaz-Delgado et al., 2003; Dixon and Barrett, 2003), which is not directly measured by the BSR.

The protective role of vegetation on dunes depends on the plants' physical characteristics (Wolfe and Nickling, 1993). Our analysis has assumed that the degree of damage done to plants by a fire (burn severity) affects the available wind impacting the surface and causing saltation (Sankey et al., 2009b). However, the estimates of burn severity from BSR show differences in green biomass loss due to fire, which may not account for the complexity of wind flow through burnt vegetation. Vegetation structures influencing wind flow (and in turn, aeolian activity) might include remnant branches and trunks not measured by vegetation indices (Wolfe and Nickling, 1993; Wiggs et al., 1994). To this end, estimates of ground cover from spectral indices such as a measure of albedo called the brightness index (BI) (Mathieu et al., 1998) or fractional cover (DeFries et al., 1995), which incorporates a spectrum of dead to living plants could be more appropriate for estimating geomorphically effective fire damage.

We speculate that the primary influences on long-term post-fire ground cover in West Australian coastal environments, in terms of re-growth, are the pre-fire cover and species distribution. As the influence of precipitation diminishes once all sites receive suitable rain, spatial and temporal patterns in recovery occur due to the existing seedbank or re-sprouting plant density (Bell, 2001; Arnan et al., 2007). For example, areas with typically sparser vegetation (e.g. Cape Le Grande or Howick) return to similarly sparse coverage (Fig. 7l). Or more broadly, the small increase in overall RR trends from west coast to south coast (Fig. 5b) might relate to a higher proportion (~50%) of reseeding plants (Bell and Loneragan, 1985; Bell, 2001; Hassell, 2001).

2.4.3 Ground cover and aeolian activity

NDVI is neither a direct measure of ground cover, nor aeolian activity. However, vegetation cover measured by SAVI (equivalent to NDVI in our context) has shown some explanatory power for aeolian activity in coastal dunefields ($r^2 = 0.4$), particularly when specific geomorphological units are considered (e.g. slip face, $r^2 = 0.6$) (Levin et al., 2006). It is possible, therefore, to make inferences from NDVI data about potential aeolian activity at a given time. Sand movement may occur while vegetation is regenerating until effective protection is re-established (Wiggs et al., 1995; Ravi et al., 2012). Sand movement during this interval is also most likely to adversely affect vegetation growth when a significant net erosion or deposition occurs (Barchyn and Hugenholtz, 2012b; Yizhaq et al., 2013). Thus, a strong recovery of QNDVI values does not rule out any sand movement. As surfaces are temporarily bare post-fire (Fig. 7k; 9), some aeolian activity is expected. However, recovery of QNDVI suggests a net change in dune form (dune mobility) has not taken place, or has been subsequently stabilised. We contend from the QNDVI recovery (and the absence of persistent bare ground in the MLC) that in none of the study sites, did substantial surface change lead to significant blowout development or dune de-stabilisation. Ravi et al. (2012) recorded rapid post-fire recovery of NDVI within three months corresponding with a sharp decrease in sediment transport flux on shrubland in Kansas, U.S.A. (Ravi et al., 2012). We infer that the same rapid decrease in aeolian activity would follow the return of biomass cover seen in WA within one to six months (Fig. 5a). We acknowledge, however, that the analysis was carried out on a 30 m spatial resolution, and small-scale surface changes would be masked by the use of a mean NDVI across entire fire polygons.

2.4.4 Monitoring the classification of bare sand

Visual inspections of classifications revealed general reliability, with some inconsistency in classifying partially vegetated surfaces (Fig. 7). Without comprehensive validation, our classifications are not rigorous enough to draw precise numerical conclusions about changes in bare sand cover. Further investigation of ideal spectral bands for use in bare ground differentiation might enhance the quality (Lu and Weng, 2007). Multiple high-resolution DEMs would then be needed to correct for shading effects on mobile dunes (Riaño et al., 2003; Hantson and Chuvieco, 2011). Confining the study to Landsat ETM+ and OLI sensors enabling pan sharpening to 15 m resolution might also improve precision. Alternatively, for coarse spatial resolutions (e.g. 30 m), classification could be substituted for within-pixel spectral indices or fractional cover (DeFries et al., 1995). For example, the BI (Mathieu et al., 1998), was shown by Levin et al. (2012) to correlate well with a high resolution image classification of bare sand on desert dunes. Classification could also be substituted by a change detection algorithm (Lambin and Ehrlich, 1997; Mas, 1999; Rogan et al., 2002). Nevertheless, accounting for limitations and complexities, the monitoring of surface change supports the NDVI results, suggesting that large changes in surface cover after fires on coastal dunes are not common (Fig. 7; 8; 9). A possible exception to this is localised blowouts seen on cleared grassland on the west coast near Wedge Island (Fig. 7d). Though they increase in size after fires, burning is not obviously the original cause. However, burning of surrounding grass cover would temporarily decrease surface roughness and likely enhance erosion rates within the blowout (Ravi et al., 2012).

2.4.5 Fire as a cause of dune de-stabilisation

Thirty fires assessed between 1988 and 2007 imply that during this period fires did not contribute to the de-stabilisation of coastal dunes. However, the correlation between precipitation and recovery has implications for the persistence of bare ground after fires in drought conditions, particularly in a steadily drying Western Australian climate (Beer, 2014; Delworth and Zeng, 2014). A reduction in vegetation growth capacity in drought conditions has been seen to prolong increased levels of aeolian activity post fire (Whicker et al., 2006). Incidentally, despite a generally drying climate, only one of the assessed fires occurred during a period of severe drought (i.e. May 1994) (Fig. 1II, 2b) (Australian Bureau of Meteorology, http://www.bom.gov.au/climate/data/). In this instance, recovery up to six months was not unusually low, though there was a 50% reduction from five to six months, possibly because of a high seedling mortality rate. After 60 months, RR had reached 1.14. It is uncertain how areas burnt during longer droughts might respond. Vermeire et al. (2005) showed that even delayed recovery due to drought does not guarantee de-stabilisation.

The results of this study on temperate coastal dunes contrast with the post-fire de-stabilisation interpreted from stratigraphy of post-glacial sub-arctic dunes (Matthews and Seppala, 2014). A common theme in the international literature is the necessity of dry or cold conditions during the post-fire period to lead to erosion (Filion, 1984; 1987; Filion et al., 1991; Seppala, 1995; Kayhko et al., 1999; Mann et al., 2002; Carcaillet et al., 2006; Matthews and Seppala, 2014). Matthews and Seppala (2014) suggest that during Holocene periods when post-fire deflation is recorded in subarctic and subalpine environments, restoration of coniferous forest cover on dunes could take several hundred years, with shrubs, grasses, lichens and mosses likely providing effect cover within a hundred years. This is a stark contrast with the recovery rates seen here in temperate and subhumid coastal heathlands. Additionally, fire regime is a potentially important variable not considered here (Keeley et al., 2011). Diaz-Delgado (2002) showed a decrease in plant community resilience after multiple fires. Climatic shifts beyond the range of temperature and precipitation of our study period, different vegetation structures, and decreased community resilience from an altered fire regime might all be requisites for post-fire de-stabilisation. An exception may be when fires are intentional. Stockton (1982) collated records of coastal dune activation in Tasmania through the 19th century, suggesting that the use of fire to clear dunes for the purpose of grazing played a key role. In this context, fire on its own had not previously activated dunes under Aboriginal burning regimes (Stockton, 1982). Rather, the addition of cattle had a profound impact by reducing surface cohesion, and possibly restricting recovery (Stockton, 1982). Barchyn and Hugenholtz (2013) suggest that reactivation of stabilised dunes requires disturbance to the whole protective covering (e.g. vegetation, roots, soil cohesion etc.). In our study, relatively bare ground apparently exists for a period of one to five months (Fig. 5b), often during the summer period of highest regional winds (Fig. 2a), and yet does not persist indefinitely. During this window, a limitation to extensive erosion might be protective elements such as soil cohesion, either physical or biocrust.

Other considerations are that fires increase the potential for erosion by water (e.g. sheetwash and gullying), particularly in temperate environments (Field et al., 2009). Fires may also temporarily increase vulnerability to other disturbances, e.g. grazing pressures or invasive species (Stockton, 1982; Levin and Ben-Dor, 2004; Sattler, 2014). Fire-related canopy clearing could act as the conduit for wind to impact the sandy surface, where another disturbance might disturb the surface itself (Wiggs et al., 1995). Alternatively, fires may be enhancing the stability of coastal dunes in WA by playing an important role in ecosystem health (Dixon and Barrett, 2003).

2.5 Conclusions

Overall, NDVI results for 30 fires spanning 28 years suggest that fires are not presently contributing to the de-stabilisation of coastal dunes in southwest WA. Recovery follows a strongly consistent pattern (75% of which is explained by a log-regression), and is characterised by rapid ground cover re-establishment within six to twelve months. Initial germination is followed by steady growth up to 60 to 80 months, where NDVI typically nears pre-fire values. We speculate that, owing to the influence of precipitation (rates and timing) on vegetation recovery (Fig. 6a), dunes may be more susceptible to post-fire erosion during dry years. This is important in a region with a drying climate such as WA. Nevertheless, despite precipitation-related delays, precipitation patterns in the last three decades have been sufficient for eventual vegetation recovery without dune de-stabilisation. While aeolian activity is likely increased post fire, major surface change did not occur prior to vegetation re-establishment. This is despite wind being sufficient to maintain other areas of active dunes, and fires often occurring during the summer period of highest regional winds and lowest precipitation. NDVI-derived estimates of burn severity were not found to be related to recovery, either due to a poor range of fire intensities, or because NDVI loss does not necessarily reflect the specific characteristics likely to impede recovery. After nine months, the biggest determinant for recovery is the pre-fire community composition and related seedbank or resprouting density.

These conclusions are supported by the classifications of bare ground. Except where fire areas were encroached by migrating dunes, cleared for development or sparsely vegetated, persistent fire-related bare ground on a coarse scale (30 m) was not seen. A notable feature was small (~60 m wide) blowouts forming on cleared grasslands on the west coast. These were likely initiated by vehicle use but possibly enhanced by the burning of a simplified and non-fire adapted vegetation. We do not rule out fires enhancing vulnerability to other disturbances (e.g. grazing, severe drought). As our study has focused on vegetation cover, further research is needed into the holistic nature of fire as a disturbance, particularly regarding soil cohesion. These results do not entirely negate the process of post-fire de-stabilisation, however, the propensity for temperate and sub-humid coastal heath vegetation to re-establish surface protection emphasises the need for extreme conditions or additional compounding disturbance in order for dunes to become active following wildfires.

2.6 Acknowledgements

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2.7 References

(See combined reference list at the end of the thesis)

Chapter 3 – Characterising the disturbance from fires on coastal dunes near Esperance, Western Australia: implications for dune de-stabilisation

Purpose: This chapter presents original research that has been undertaken entirely within this MRes year. The chapter provides an introduction, methods, results and discussion related to the disturbance caused by recent fires on coastal dune systems near Esperance, Western Australia (WA). The findings presented in this chapter are central to this thesis and build upon the information discussed in Chapter 2 by providing a local scale assessment of the dynamics of wind, surface characteristics and aeolian activity in the post-fire environment, as well as local short term patterns of recovery. This chapter will address aims iv, v, vi and vii highlighted in the introductory chapter.

Format: In accordance with the Macquarie University policy for higher degree research thesis by publication[2] this chapter has been written for submission to a peer-reviewed journal (*Aeolian Research).* Repetition and any referencing and stylistic inconsistencies have been minimised to facilitate the thesis examination process. Supplementary material and references referred to in the paper are provided in the reference list and appendices at the end of the thesis, and are intended to become the references and supplementary material provided in the published version of this paper.

Author contributions: The authors of this paper and their contributions are as follows:

Samuel Shumack carried out fieldwork and sampling with P.H., conducted mapping, analysed and interpreted data, designed and drafted all figures and tables, and wrote and edited the paper.

Paul Hesse developed the study with S.S., carried out fieldwork and sampling with S.S., designed some figures with S.S., provided comments on the paper, and supervised S.S. in the research.

[2] The Macquarie University policy for thesis by publication states that a thesis may include a relevant paper or papers that have been published, accepted, submitted or prepared for publication for which at least half of the research has been undertaken during enrolment. The papers should form a coherent and integrated body of work. The papers are one part of the thesis, rather than a separate component (or appendix) and may be single author or co-authored. The candidate must specify their contribution and the contribution of others to the preparation of the thesis or to individual parts of the thesis in relevant footnotes/endnotes. Where a paper has multiple authors, the candidate would usually be the principal author and evidence of this should appear in the appropriate manner for the discipline. MQ Policy: http://www.mq.edu.au/policy/docs/hdr_thesis/policy.html

Characterising the disturbance from fires on coastal dunes near Esperance, Western Australia: implications for dune de-stabilisation

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Abstract

This paper aims to characterise fires on coastal dunes concerning surface disturbance and aeolian activity. Fire is commonly listed as a contributing disturbance to dune deflation events. If de-stabilisation is to occur, destruction of vegetation must be sufficient to break the protective skin of the dune uncovering loose sediment. This paper reports on field data collected in February 2016 at two sites on coastal dunes near Esperance, Western Australia (WA) after recent wildfires in November 2015 (near Wylie Bay) and January 2016 (behind Quallilup Beach). We assessed whether and how the remnant burnt covering acts to protect the surface by measuring wind profiles at burnt and unburnt sites, recording evidence of recent sand movement, and assessing the burnt and control surfaces in terms of protective covering and burn severity. We also used remote sensing and on-site photos to monitor local patterns of short term biomass recovery. Results suggest that wind flows through burnt vegetation without the turbulence seen above dense vegetation. Speed-up ratios (SR) increased by 5 to 120% from vegetated to burnt surfaces. However, burnt vegetation did not show the same topographic acceleration observed on bare dunes. This decelerating effect was proportional to the level of remaining ground cover ($r^2 = 0.8$). Increase in erosion and surface sand movement after fires was evident (≤ 30%). Despite these increases in ripple cover post-fire, values were significantly less than ripple cover on previously-bare surfaces (by 60 to 100%). This was most obviously due to ground cover ($r^2 = 0.95$), which protects the surface and reduces wind availability, although soil cohesion may have also been restricting sand movement. Effective ground cover appears to be >40%. At Quallilup, burn severity assessment revealed little remaining protective woody structure. The burn intensity may have inhibited short term germination and re-sprouting, despite adequate precipitation. The implications are that fire as the sole disturbance is not a major threat to the stability of these coastal dunes, with the possible exception of extreme burn intensities where ground cover re-establishment is inhibited and the dune becomes susceptible to further non-fire disturbance events.

Key words: Fire, dune, de-stabilisation, coastal, aeolian, geomorphology

3.1 Introduction

Coastal sand dune systems are dynamic environments, sometimes active with shifting sand, sometimes stabilised by plant growth, and often a mix of both (Hesp, 2013). Transitions from stable dunes to active dunes, termed ‘re-activation’, has been observed but is not well understood (Barchyn and Hugenholtz, 2013). A hysteresis in dune behaviour occurs in response to environmental drivers, meaning significant change is needed for a shift in dune activity (Tsoar, 2005). This may be gradual change (e.g. wind climate), or abrupt disturbance (e.g. storms) removing vegetation and leaving the surface susceptible to erosion by wind (Hesp and Martinez, 2007; Barchyn and Hugenholtz, 2013). Where this erosion forms a topographic depression known as a blowout, it may then develop into a substantial 'transgression' of sand moving parallel to the dominant wind direction (Barchyn and Hugenholtz, 2013; Hesp, 2013; Yizhaq et al., 2013). However, the nature and precise role of the disturbances necessary for destabilisation are poorly defined (Barchyn and Hugenholtz, 2013). Common suggestions include stock grazing, feral animal grazing (e.g. rabbits), drought, cyclones (or other storm-related foredune scarping), geomorphic changes (e.g. sand supply), anthropogenic disturbances, and fire (Conacher, 1971; Martini, 1981; Pye, 1982; Christensen and Johnsen, 2001; Hesp, 2002; Wiles et al., 2003; Lepczyk and Arbogast, 2005; Buynevich et al., 2007; Barchyn and Hugenholtz, 2013; Yizhaq et al., 2013; Ruz and Hesp, 2014). Barchyn and Hugenholtz (2013) propose that multiple disturbances are likely necessary. Fire is commonly listed as a significant contributing disturbance to deflation events, particularly when combined with certain climate phases (Filion, 1984; Filion, 1987; Filion et al., 1991; Seppala, 1995; Kayhko et al., 1999; Mann et al., 2002; Carcaillet et al., 2006; Matthews and Seppala, 2014). Indeed, the monitoring of post-fire soil erosion in grasslands and on dunes has shown increases in the saltation of sand grains (Zobeck et al., 1989; Whicker et al., 2002; Vermeire et al., 2005; Sankey et al., 2009a; 2009b; Ravi et al., 2012; Stout, 2012). However, contemporary observations often show that where dune vegetation is burnt, no significant landscape changes take place (Vermeire et al., 2005; Ward, 2006; Myerscough and Clarke, 2007; Levin et al., 2012).

With the broader goal of understanding the role that fires might play in destabilising dunes, the aim of this paper is to explore the nature of the disturbance to vegetated dune surfaces after fires. Barchyn and Hugenholtz (2013) suggest that destruction of vegetation must be sufficient to break the protective skin of the dune and uncover bare and loose sediment. This includes aboveground biomass (covering the surface and reducing wind speed), and soil cohesion provided by roots, biogenic crusts, and soil properties (Wolfe and Nickling, 1993; Barchyn and Hugenholtz, 2013). Similarly, Arens et al. (2007) hold that dune activity is determined by the availability of loose sand, the capacity for vegetation to grow and offer protection, and the strength of sand-moving winds. Thus, post-fire erosion can be related to the degree of protection and wind-obstruction provided by remnant burnt vegetation and litter, and the post-fire soil cohesion (Wolfe and Nickling, 1993; van Dijk et al., 1999; Barchyn and Hugenholtz, 2013). These factors influence the availability of sediment, and the application of wind force to the surface. Additionally, the short-to-medium term state of the post-fire surface coverage is strongly influenced by ecological processes, particularly regeneration patterns and rates associated with dominant or significant species present (Díaz-Delgado et al., 2003; Myerscough and Clarke, 2007). These factors can be assessed with ground cover surveys and wind measurements on burnt sites and unburnt control sites, supplemented with measurements of post-fire aeolian activity. This combination has been used to effectively characterise post-fire disturbance in desert settings in the Kalahari (Wiggs et al., 1994) and Central and Western United States (Whicker et al., 2002; Miller et al., 2012). These studies reported decreased ground cover and drag effect on wind, and increased aeolian activity on burnt sites, but with no blowouts occurring during the study periods. However, the characteristics of fires differ greatly between climatic regions (Bowman et al., 2009), and no such study has been done on temperate or coastal dunes.

To test the hypothesis that fire plays a role in dune de-stabilisation, this paper reports on field data collected at two sites on coastal dunes near Esperance, Western Australia (WA) after recent wildfires. We assessed whether and how the remnant covering is acting to protect the surface by measuring wind profiles at selected burnt and unburnt sites, as well as recording evidence of recent sand movement. We also assessed burnt and unburnt surfaces to measure relevant protective covering and burn severity. Furthermore, we used remote sensing and on-site photos to monitor short term biomass recovery. The two sites surveyed in February 2016 had been burnt in November 2015 and January 2016 respectively with different intensities. This allowed comparison of disturbance from fires with higher and lower burn severities.

3.2 Materials and methods

3.2.1 Study area

Coastal dunes to the east and west of Esperance, WA exist on a coastal terrain of gneissic and granitic bedrock hills amidst Cainozoic and Quaternary sediments (Fig. 1) (Semeniuk and Semeniuk, 2011). The reworking of shore-sediments has formed large calcareous dunefields with complex parabolic, star and barchan forms (Fig. 1) (Semeniuk and Semeniuk, 2011). Dunes east of Esperance overlie a Holocene higher sea-level deposit forming a cemented calcrete sheet at the level of the once higher water table (~2 m above present sea level). These sheets are occasionally exposed in active dune areas (Semeniuk and Semeniuk, 2011). Blowouts and active dunes persist despite disconnection from the beach and associated sediment delivery (Overheu et al., 1993). Road cuttings expose buried soil profiles indicative of multiple phases of recent dune activity (Overheu et al., 1993). Stabilised dunes are typically complex long-walled parabolic forms (Overheu et al., 1993). Older, less well-defined, Pleistocene dunes are oriented east-west, and have lithified calcrete cores (Overheu et al., 1993). Some areas of dune swales were cleared for grazing after European settlement but have since been abandoned to hobby farms and residential areas (Overheu et al., 1993). Several existing blowouts are presently accessible for recreational 4WD and All-Terrain Vehicle (ATV) use. The Holocene parabolic dune vegetation has been characterised as tall closed shrubland dominated by *Leucopogon parviflorus* and *Acacia sp.*, while the dune swales exhibit low closed shrubland dominated by *Acacia sp.* (Overheu et al., 1993). The Esperance region experiences an average annual rainfall of 617 mm (1969-2016), peaking in July, with the lowest rainfall occurring from December to January (Australian Bureau of Meteorology, www.bom.gov.au/climate/data/). The annual mean maximum temperature is 21.9ºC, peaking at 26.2 ºC through January and February. Regional winds are strongest in December through to February (mean 3pm speed = 29.2 km/h).

During the Western Australian fire season of 2015/16, two fires burned extensive areas of coastline near Esperance, WA. On 17 November 2015, a lightning strike sparked a fire 13 km east of Esperance, near Mullet Lakes. Over several days approximately 14240 ha of land burned with moderate intensity through reserve areas and some rural properties behind Wylie beach between Esperance and Cape le Grande (Fig. 1). On 4 January 2016, a second lightning fire burned 13500 ha from 10 km west of Esperance (near Pink Lake,) through unmanaged reserve and National Park land across 35 km of coastline behind Quallilup Beach. This fire had a comparatively high intensity. Aside from some cleared land, both fires were confined to uninhabited areas of coastal dune heath vegetation. The fires burnt extensive areas of dune moving toward the coastline up to the lee slope of the foredunes, leaving the crest and stoss slope of the foredunes relatively unburnt (Fig. 1a; 1b).

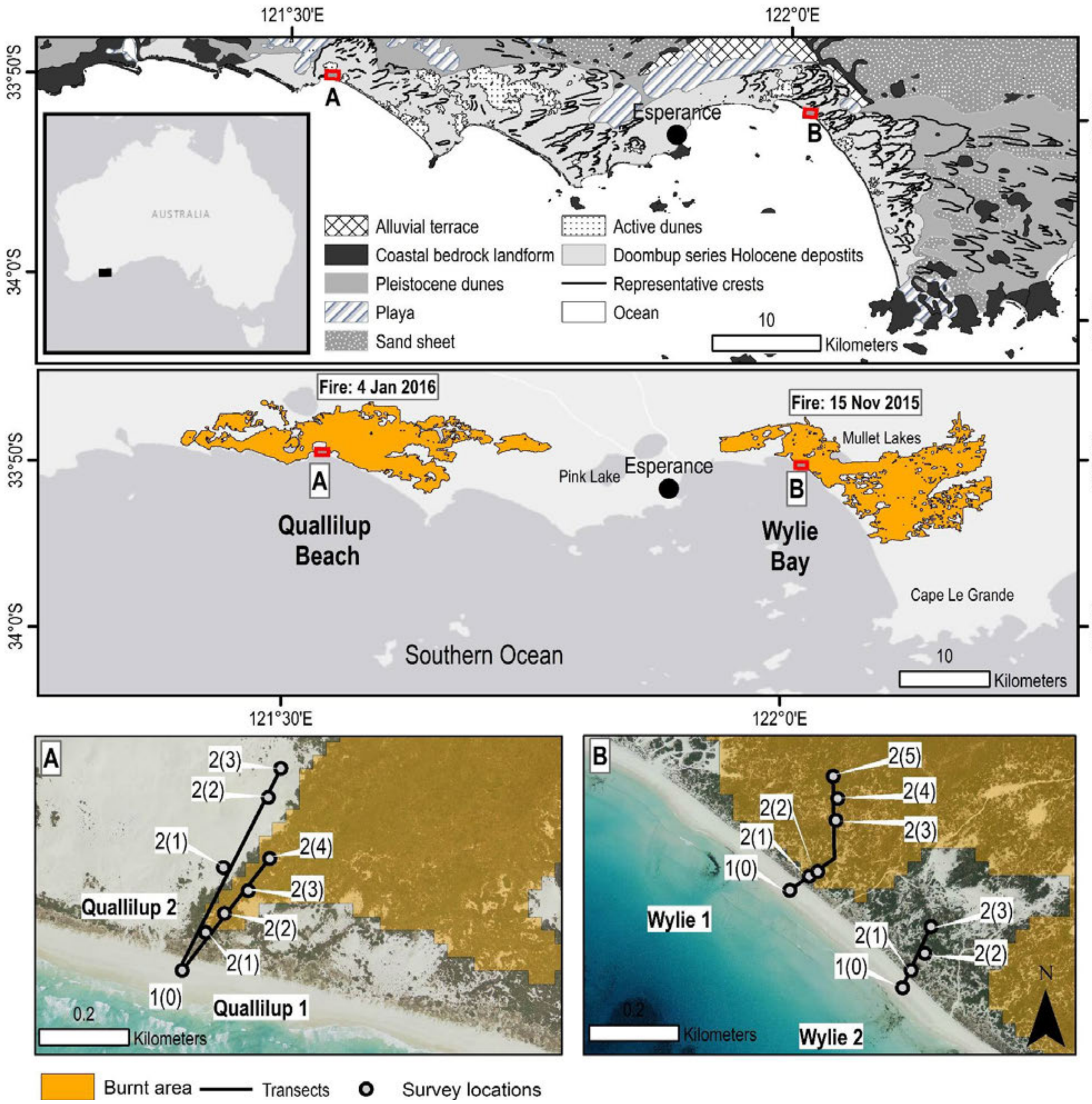

Figure 1: Maps showing locations of field sites in relation to regional geomorphology and boundaries of fire-scars. Locality maps show survey transect locations over dune areas with different surface conditions. (A) Quallilup Beach – (1) bare and (2) high severity burn. (B) Wylie Beach – (1) moderate severity burn and (2) unburnt vegetation.

3.2.2 Methods

Vegetation and ground cover

From 10-15 February 2016, data were collected along four separate transects shown in Figure 1a; b. At Quallilup Beach one transect ran across an area of previously vegetated dune, burnt with a high intensity (Q1), and one transect ran across a currently active dune (Q2) (Fig. 1a). At Wylie Bay we ran transects across an area burnt with moderate intensity (W1), and along a remnant patch of unburnt dune with heath vegetation (W2) (Fig. 1b). Wind profile and vegetation measurement locations along each transect were chosen to represent key dune features (e.g. foredune crest, interdunes, windward slopes, and inland dune crests).

Following the approach of Hesse and Simpson (2006), we used point intercept vegetation and ground cover surveys. We designed the grid of points to extend further along-wind than across-wind (relative to the dominant onshore winds). Figure 2b depicts our survey design with nine points spaced at 1 m across constituting a row, and five rows per anemometer location spaced 5 m apart. At each transect point we assessed all relevant protective covering. Following Miller et al. (2012), who similarly compared burnt and unburnt sites, and Hesse and Simpson (2006), we recorded live and dead plants, live and dead canopy, litter cover, bare ground and the presence of soil crusting (up to a depth of 100 mm beneath loose sand). Where possible we identified plant species to better understand the potential recovery of ground cover (Díaz-Delgado et al., 2003).

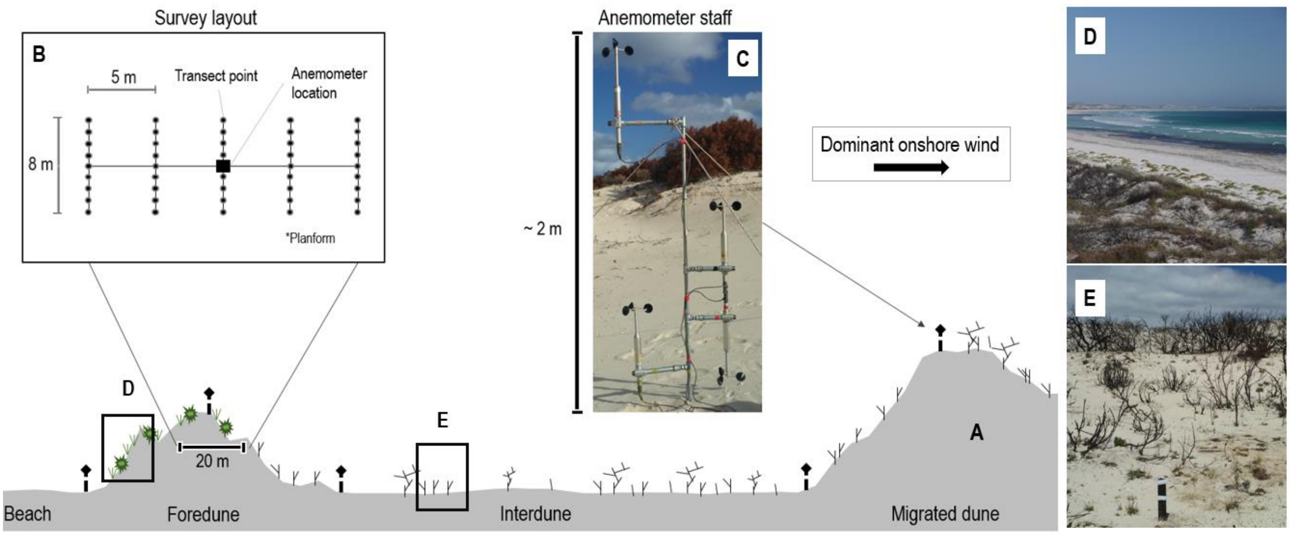

Figure 2: (A) Schematic cross section showing remnant burnt trunks and branches with a relatively unburnt foredune. (B) Survey design centred on anemometer staff extending along-wind. (C) Anemometer setup (photo from bare site Q2-2(3)). (D & E) Example images of unburnt foredune (D) and burnt interdune area (H).

Our survey excluded a lateral dimension for roughness elements. Thus, we could not calculate plant silhouette area, commonly termed lateral cover (L_c), roughness density (λ) or frontal area index (FAI), which have been related to wind profile parameters and aeolian activity (Wolfe and Nickling, 1993; Wiggs et al., 1996; Lancaster and Baas, 1998; Hesse and Simpson, 2006). As a surrogate for FAI estimates, we took the average canopy height of all points upwind (seaward) of anemometer locations. Included in this average were points with no vegetation (values of zero). In this way, the average depends on typical plant heights, but also expresses an element of plant cover density. In the absence of true estimates of the lateral cover of plants, this provides a coarse relative measure of the plant structure facing the dominant wind. Hereafter this is termed the 'pseudo Frontal Area Index' (*p*FAI). To further quantify variation in the structure of remnant vegetation, because of differences in fire intensity, we assessed the burn severity of each survey row by appearance. Following Diaz-Delgado et al. (2003), we assessed each survey row with the scale in Table 1. Our *p*FAI measurements, and other more typical lateral cover estimates do not account for differences in plant structure (e.g. shape or porosity) (Hesse and Simpson, 2006). This is especially pertinent where burnt plants with few or no leaves or branches were recorded. We attempted to coarsely normalise *p*FAI values (calibrated *p*FAI) using the estimates of burn severity to incorporate the diversity in remnant protective cover using Equation 1. Note that this still does not account for any variation in plant structure at the vegetated site Wylie 2.

$$Calibrated\ pFAI = pFAI/Burn\ severity \quad (1)$$

Table 1: Scale of burn severity adapted from Diaz-Delgado et al. (2003)

Burn severity scale	Description
1	Not burnt
2	Ground fire
3	Canopy partially green
4	Burnt trees with remnant burnt leaves
5	Burnt trees with fine branches across all of the trunk
6	Burnt trees with fine branches only near the top of the trunk
7	Burnt trees with no fine branches
8	Burnt trees with only a trunk
9	Burnt trees with only a stump

Aeolian activity

Following the approach of Hesse and Simpson (2006), we used ripple features as an indicator for recent aeolian activity, and the depth of loose sand covering an underlying crust as an indicator of sediment availability. The presence or absence of loose sand may also indicate recent deposition or erosion respectively. Ripples are likely preserved between occurrences of sand-moving winds, and are easily comparable between sites (Hesse and Simpson, 2006). For logistical reasons, we were unable to take repeat measurements on erosion pins (e.g. Wiggs et al., 1995; Whicker et al., 2002), nor could we directly measure saltation in the field (e.g. Whicker et al., 2002; Miller et al., 2012). Surface soil samples were taken for lab analysis of particle size, organic matter and carbonate content (see Appendix 5 for details of analysis methods).

Wind profiles

Following Wiggs et al. (1996), we simultaneously used two anemometer arrays. One reference staff was placed on the beach (Gares and Nordstrom, 1995), the other moved between appropriate locations in the dune fields every 30 minutes (Fig. 2). Each staff had Met One cup anemometers at heights of 0.1, 0.55, 1.0, and 2.0 ± 0.05 m (Fig. 2). The number of anemometers and the maximum height were restricted by instrument availability. At some locations more than one anemometer was below the canopy. A reading at ~0.1 m enabled comparisons of surface winds effective in moving sand. Simultaneous readings at the beach and dune sites enabled the calculation of a speed up ratio (SR), adapted from Wiggs et al. (1996):

$$SR = \frac{(u_z - u_r)}{u_r} \times 100 \tag{2}$$

where u_z = velocity measured on the roving staff at height z, and u_r = reference velocity at height z. The SR represents a percentage difference between velocities on the beach (bare, flat surface) and dune (rough, undulating surface) (Wiggs et al., 1996). SR normalises temporal variations in regional horizontal velocity (u_h) experienced during measurement, and highlights surface-related differences.

Shear velocity (u_*) (boundary friction formed as wind moves over rough surfaces) was derived from profiles to assess the drag effect of burnt and unburnt vegetation (Wolfe and Nickling, 1996). This is theoretically useful in comparing the erodibility of surfaces (Whicker et al., 2002). In the absence of three-dimensional anemometry, we extracted u_* from the theoretical log-linear profile termed the 'Law of the Wall' (Bagnold, 1941; Wolfe and Nickling, 1993; Whicker et al., 2002):

$$u_z = \left(\frac{u_*}{k}\right) \ln\left(\frac{z}{z_0}\right) \tag{3}$$

where u_z is the velocity at height z, z_0 is the roughness length, and k is the von Karman constant [or von Karman parameter (Sherman et al., 2013)]. The reliability of this estimation depends on vertical wind profiles fitting a log-linear regression model (Bagnold, 1941). The logarithmic profile is significantly altered within the roughness sublayer by vegetation (e.g. Wolfe and Nickling, 1993; Wiggs et al., 1996) and by complex dune topography (e.g. Gares and Nordstrom, 1995; Frank and Kocurek, 1996; Hesp and Hyde, 1996; Wiggs et al., 1996; Fraser et al., 1998; Hugenholtz and Wolfe, 2009; Smyth et al., 2012). The shape of wind profiles below canopy in dense natural vegetation is complex, not well understood, and likely not logarithmic (Wolfe and Nickling, 1993). We could not, therefore, reliably extract surface u_* from densely vegetated sites. For profiles with weaker correlations (<0.95) attributed to topographic acceleration (e.g. Quallilup 1-1(3); 2-2(2-3)), we derived parameters from only the points within the internal boundary layer. Since u_* has a site-specific proportionality to u_h (Whicker et al., 2002), where possible temporal variations in u_h during measurement were accounted for by extracting linear relationships between u_* and u_h for each site. To do this, we extracted u_* from a minimum ten one-minute-average velocity profiles, and plotted these against respective u_h measured at 2 m above ground. This could not be achieved where near-surface wind profiles were too obstructed by internal boundary layer formation or dense vegetation. We hereafter show u_* calculated using a nominal wind speed of 5 ms^{-1} at 2 m above ground.

Remote sensing and site observations

We obtained eight Landsat 8 Operational Land Imager (OLI) images with 30 m resolution captured from November 2015 through to August 2016 (see Appendix 6). The Normalised Difference Vegetation Index (NDVI) has been widely used to track post-fire biomass recovery in heathlands and elsewhere (Henry and Hope, 1998; Díaz-Delgado et al., 2002; Díaz-Delgado et al., 2003; Hope et al., 2007; Levin et al., 2012; Ravi et al., 2012; Lu et al., 2015). The absorption of red visible light (R) and reflection of near infrared (NIR) by chlorophyll enables the estimation of biomass in a multispectral image pixel using the following equation (Tucker, 1979):

$$(NIR - R)/(NIR + R) \tag{4}$$

We monitored NDVI at burnt sites W1 and Q1, and vegetated site W2. NDVI values can be affected by soil properties and seasonal changes in phenology (Huete, 1988; Jackson and Huete, 1991; Díaz-Delgado et al., 2002; Hugenholtz et al., 2012). However, Levin et al. (2012) observed that the seasonality of NDVI diminishes after a fire and is not restored until ground cover is well established. For this study, we are only concerned with the first six months of recovery, and consistent surface soil properties across all sites (see Appendix 5) should allow for a reliable estimate of relative biomass. Daily and monthly precipitation rates through the period of NDVI assessment were obtained to aid interpretation. A difference NDVI image (dNDVI) was also produced between NDVI pre-fire ($NDVI_{PREFIRE}$) and NDVI post-fire ($NDVI_{POSTFIRE}$) to aid with mapping fire scars (Equation 5) (Díaz-Delgado et al., 2002; Morgan et al., 2014; Lu et al., 2015). We calculated a Burn Severity Ratio (BSR) between the loss of biomass signal (dNDVI) and the pre-fire NDVI (Equation 5). We then calculated a Recovery Ratio (RR) between the recovery in biomass since the fire [expressed as the difference between NDVI immediately post-fire ($NDVI_{POSTFIRE}$) and recovered NDVI at point T ($NDVI_T$)] and the amount which was initially lost (dNDVI) [adapted from Levin et al. (2012)] (Equation 6). Results were correlated with on-ground assessment of burn severity and used to explore the influence of local burn severity variations on recovery.

$$dNDVI = NDVI_{PREFIRE} - NDVI_{POSTFIRE} \tag{5}$$

$$BSR = \frac{dNDVI}{NDVI_{PREFIRE}} \tag{6}$$

$$RR = \frac{(NDVI_T - NDVI_{POSTFIRE})}{dNDVI} \tag{7}$$

We placed six pins in the ground at survey locations W1-2(2), W1-2(3), W1-2(4), Q1-2(1), Q1-2(3) and Q1-2(4) as a reference for on-ground monitoring of recovery. These locations were photographed on 15 February 2016. Follow-up photos were taken at pin locations Q1(2,3,4) on 26 June 2016, and W1(2,3,4) on 27 June 2016 by Kenneth Mills, Esperance Wildflower Society (pers. comm., 2016).

3.3 Results

3.3.1 General site characteristics

Results of the burn severity assessment confirmed that the reported higher intensity burn at Quallilup Beach caused more physical damage to vegetation structure (Table 2). Much of the woody structure of shrubs had burnt off, the taxonomy of remnant stumps was unidentifiable, and the average canopy height seemed to be significantly reduced (although we did not survey adjacent healthy vegetation) (Table 2). At Wylie Bay, which reportedly experienced a less intense burn, burnt plants were more often identifiable, retaining average structural heights (0.3 to 1.33 m) similar to nearby unburnt vegetation (0.56 to 1.24 m) (Table 2). Both foredunes surveyed [W1-2(1) and W2-2(1)] had populations of the invasive weed *Euphorbia paralias*, and other smaller shrubs. Beyond the foredune, average canopy height increased (except at W1-2(3) where pre-fire vegetation was sparse), and larger species (e.g. *Acacia cyclops*) become abundant (Table 2).

The sand in the region is typically medium grain size, and is slightly larger at Quallilup Beach (~290 µm), than at Wylie Bay (~240 µm) where wave energy is lower. Surface carbonate content (mostly in the form of shell fragments) ranges from 14% on a parabolic dune [W1_2(4)] to 30% on the foredune [W2_2(1)]. Top soils contained between 1 and 3% organic matter (see Appendix 5 for detailed surface soil characteristics).

Table 2: Summary of survey site characteristics.

Survey sites	Dune setting	Condition (& burn severity)	Common flora	Average canopy height (m)
W1_1(0)	Beach face	Bare	-	-
W1_2(1)	Foredune crest	Burnt (2.6)	Cyperaceae, *Euphorbia paralias*	0.52
W1_2(2)	Interdune	Burnt (5.2)	*Leucopogon sp., Acacia cyclops*	0.94
W1_2(3)	Interdune	Burnt (3.6)	*Leucopogon sp., Scaevola crassifolia*	0.3
W1_2(4)	Dune crest	Burnt (5)	*Acacia cyclops*	1.33
W1_2(5)	Dune crest	Burnt (5.4)	*Acacia cyclops, Leucopogon sp.*	0.95
W2_1(0)	Beach face	Bare	-	-
W2_2(1)	Foredune crest	Unburnt	*Euphorbia paralias, Scaevola crassifolia*	0.56
W2_2(2)	Interdune	Unburnt	*Scaevola crassifolia,* Cyperaceae	0.71
W2_2(3)	Dune crest	Unburnt	*Lepidosperma gladiatum, Spyridium globulosum, Scaevola crassifolia, Acacia cyclops*	1.24
Q1_1(0)	Beach face	Bare	-	-
Q1_2(1)	Dune crest	Burnt (7)	Unidentified burnt stumps*	0.09
Q1_2(2)	Interdune	Burnt (7)	Unidentified burnt stumps*	0.02
Q1_2(3)	Upwind slope	Burnt (7)	Unidentified burnt stumps*	0.05
Q1_2(4)	Dune crest	Burnt (7)	Unidentified burnt stumps*	0.3
Q2_2(1)	Interdune	Bare	*Euphorbia paralias*	0.03
Q2_2(2)	Upwind slope	Bare	-	-
Q2_2(3)	Dune crest	Bare	-	-

*Species found in unburnt vegetation on Quallilup dunes near to survey sites included: *Acacia cyclops*, *Acacia cochlearis*, *Scaevola crassifolia,* and *Spyridium globulosum*

3.3.2 Wind measurements

Onshore winds measured on the beach face at each site show only subtle deviations from a log-linear profile indicating minimal surface roughness and well developed boundary conditions (Fig. 3). Moderately burnt Wylie 1 shows generally stable logarithmic wind profiles within the burnt canopy, except at W1-2(5) where an internal boundary layer acceleration may be slope-related (Fig. 3a). W1-2(2, 3, and 5) show higher SR below the canopy of burnt vegetation (average ~.9 m) than above it (Fig. 3a). At W1-2(3) a lower average canopy height results from a patch of ground apparently bare pre-fire (Fig. 3a; 8). Acceleration over this bare ground and up the base

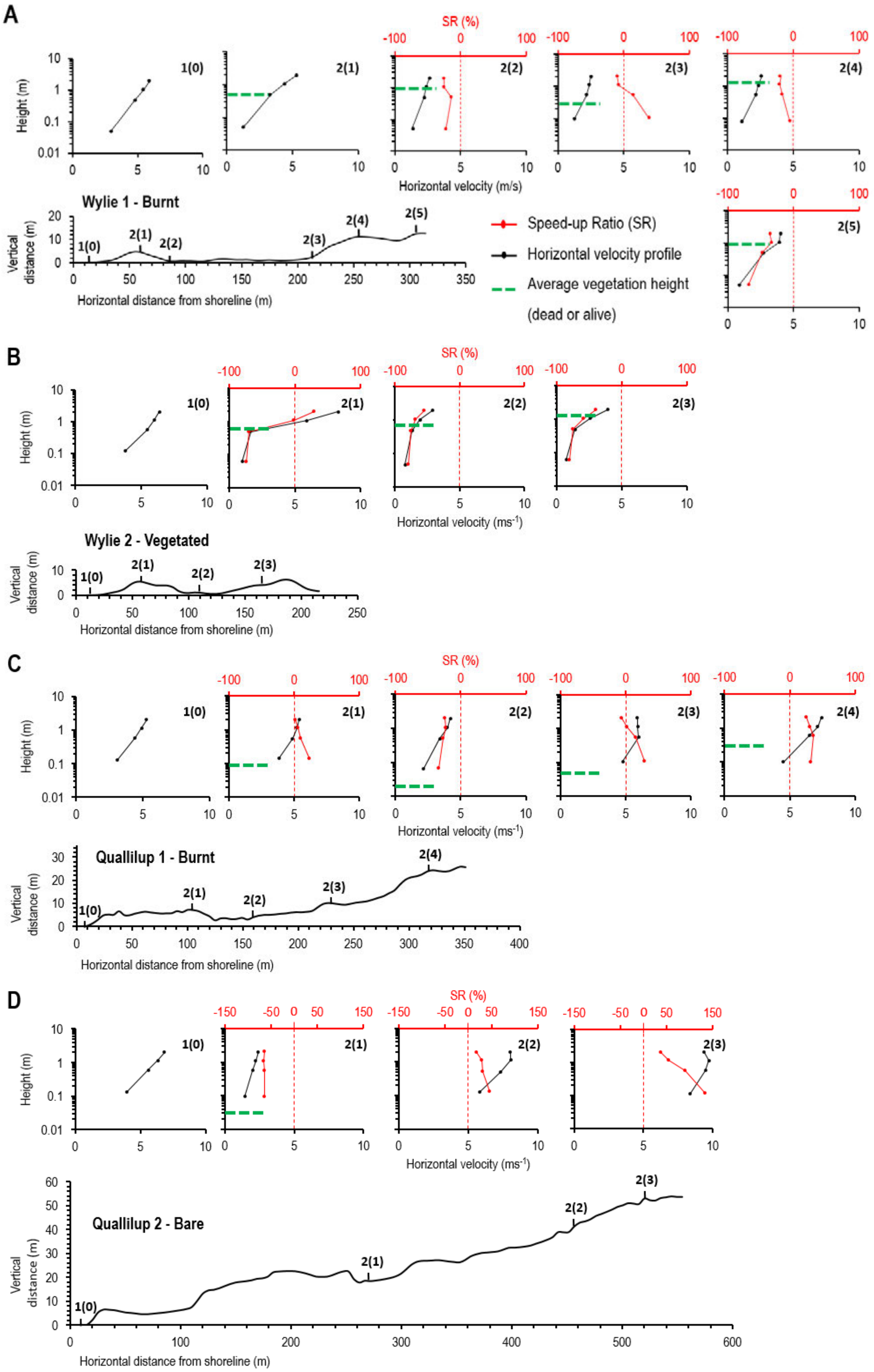

Figure 3: Horizontal wind velocity profiles and Speed-up Ratios (SR) relative to point 0 (beach face) for onshore winds. Graphs labelled 0-4 show results of wind measurements taken at corresponding points marked on topographic cross sections below for each site. Sites: (A) Wylie 1, (B) Wylie 2, (C) Quallilup 1, and (D) Quallilup 2. At Wylie 1 (A), SR values at W1-2(1) were excluded due to a dominant offshore wind during measurement.

of the dune slope causes a positive SR on the lower half of the profile (Fig. 3a). Overall SR values at Wylie 1 are generally negative (Fig. 3a). Reasons for the inverse SR profile are unclear. At the vegetated site Wylie 2 (W2), downwind SR values are generally negative except above 1 m on the foredune crest W1-2(2) (Fig. 3b). Here, the profile shows rapid acceleration above the roughness sub-layer formed by short, dense vegetation which may represent a displacement height <1 m (Fig. 3b). At sites W2-2(2) and W2-2(3) SR and u_h below 1 m are similarly drastically reduced (Fig. 3b). Taller vegetation coincides with comparatively less acceleration above 1 m (Fig. 3b). Here, measurements are almost entirely within the roughness sub-layer (Fig. 3b).

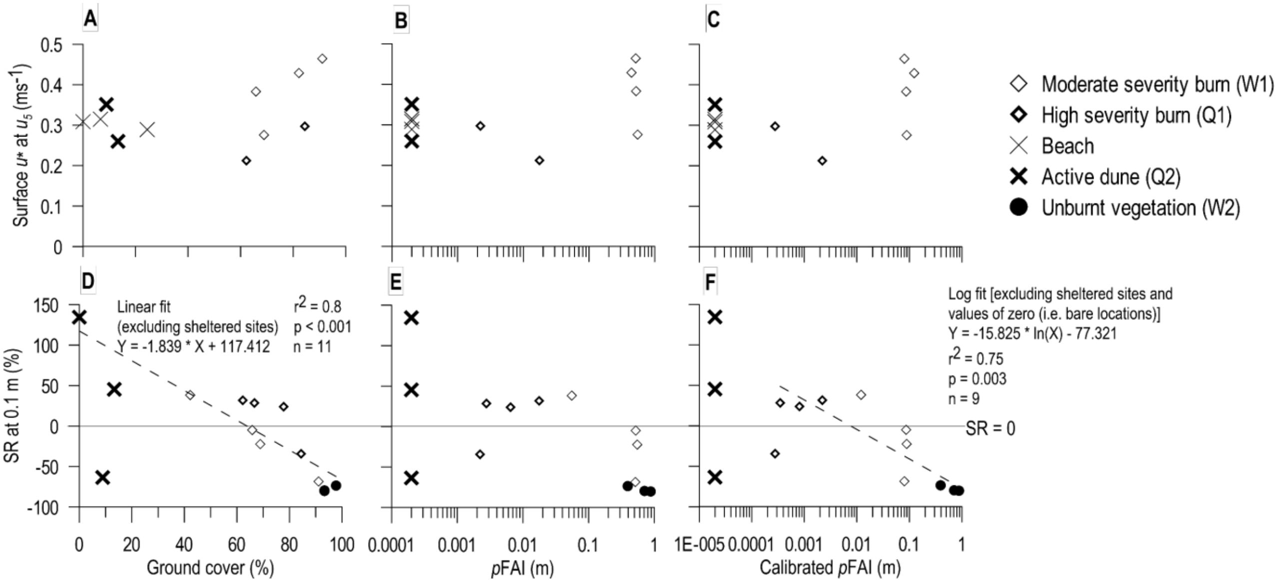

Figure 4: Explanatory power of survey results for wind parameters. Top: Surface u_* at u_5 (i.e. u_* when u_h = 5 ms^{-1}) taken from log-linear profiles plotted against: (A) ground cover; (B) upwind pseudo Frontal Area Index (*p*FAI); and (C) upwind calibrated *p*FAI. Bottom: Speed-up Ratio (SR) measured at 0.1 m above ground plotted against (D) ground cover; (E) upwind *p*FAI; and (F) upwind calibrated *p*FAI. For SR at 0.1 m, interdune sites [W1-2(2), W2-2(2), Q1-2(2), and Q2-2(1)] are shown but excluded from the regression analysis due to topographic sheltering. Results of *p*FAI are plotted on a log scale, with values of zero (i.e. bare sites) being shown as 0.0002 for *p*FAI and 0.00002 for calibrated *p*FAI. For calibrated *p*FAI, bare sites are shown but not included in the regression because values of zero could not be log-transformed.

At the severely burnt Quallilup 1 (Q1), lower lying sites 2(1) (migrated foredune) and 2(2) (interdune) show near log-linear profiles indicative of stable conditions (Fig. 3c). However, disruptions of the log-linear profile did occur on the foredune [Q1-2(1)]. SR at Q1-2(1) suggests some topographic acceleration up the foredune (Fig. 3c). Q1-2(2) shows a negative SR, characteristic of other interdunes (Fig. 3c). Up-slope measurements at Q1-2(3) and Q1-2(4) show near-surface acceleration within a developing boundary layer associated with the rising slope (Fig. 3c). The profile shapes at Q1 do not show strong signs of boundary friction being imparted on the wind by the remnant burnt stumps (Fig. 3c).

Wind profiles at Q2 are similar in shape to those at Q1. Q2-2(1) shows stable and reduced wind flow sheltered from onshore winds within the interdune (Fig. 3d). Up-slope Q2-2(2) and Q2-2(3) show kinked profiles indicating inner boundary layer development over the smooth sloping surface (Fig. 3d). The SR values at Q2-2(2) indicate topographic acceleration (20-50%) within 1 m before decreasing to ~10% at 2 m above internal boundary layer. Wind at the crest [Q2-2(1)] is similar, though SR at 0.1 m is more extreme (150%), dropping to 40% at 2 m. At the time of measurement, high rates of saltation could be observed. Here we do not consider the influence of saltation on near-surface wind flow. SR values on the slope and crest of Q2 are higher than the corresponding slope and crest at Q1 (Fig. 3c; d). This could mean the remnant burnt vegetation is inhibiting topographic acceleration. However, both Q2-2(2) and Q2-2(3) are elevated above all Q1 sites (Fig. 3c; d), so simple height difference is a possible explanation. At all sites but one [W1-2(1) – excluded due to offshore winds], the speed up ratio is greater at crests than at preceding interdunes (Fig. 3). This difference is greatest for the bare dune, and smallest for the vegetated dune (Fig. 3).

Figure 4 explores the explanatory power of survey results hypothesised to influence wind parameters (see Appendix 4 for full table of survey results). For u_* there appears to be a small increase in turbulent flow at two moderately burnt locations (Fig. 4a). Mostly, however, near-surface u_* values fall within a range (0.2 to 0.4 ms^{-1}) with no apparent influence from measures of ground cover or silhouette area (Fig. 4a; b), even when silhouette area is calibrated for the burn severity (Fig. 4c), and without clear distinction between site characteristics. Where u_* represents the character of near-surface wind-flow, SR represents the availability of wind energy allowed by site characteristics. Figure 4 shows a stronger relationship between surveyed vegetation and SR than with u_*. Of the chosen parameters, SR was most influenced by ground cover (Fig. 4d; e; f). Any influence of *p*FAI appears weak and scattered, in part because *p*FAI is almost equivalent for moderately burnt and vegetated despite different SR values (Fig. 4e). When *p*FAI is calibrated for burn severity, the explanatory power improves (Fig. 4f). The data does not immediately show a significant correlation, however, the influence of topographic sheltering on SR shown in Figure 3 may account for this. Location Q2-2(1) was especially well-sheltered by a steep upwind slope (Fig. 3d). When this outlier (-60%) is removed, the relationship for ground cover increases to r^2 = 0.82. When all interdune readings are removed, r^2 = 0.8 for 11 ground cover locations, and r^2 = 0.75 for the nine remaining calibrated *p*FAI locations (after a log-transformation of calibrated pFAI and removing values of zero). These coefficients represent the influence of vegetation on the topographic speed-up of wind (Fig. 4d). Within this relationship, we see the separation of locations according to fire-related surface characteristics, where a decrease in *p*FAI and ground cover post fire causes an increase in SR. Note that several severely burnt sites have similar SR values to the stoss slope of the bare dune (Fig. 4c; d).

3.3.3 Influences on sand movement

Considering the relationship between wind parameters and ripple cover within burnt and vegetated sites; u_* has no significant correlation, while SR appears to have some explanatory power (r^2 = 0.84) (Fig. 5a; b). As SR increases from vegetated to burnt, ripple cover increases (Fig. 5b). However, Figure 5 shows a clustering of points in the low range of ripple cover (0-30%) for all sites previously vegetated, and significantly higher values for pre-existing bare ground (~90-100%). There is an increase in ripple cover between vegetated W2 (0%) and burnt W1 & Q1 (1-30%), with no clear distinction between severely and moderately burnt for any single parameter (Fig. 5). Once ripple cover reaches 100% at bare sites, the index for sand movement reaches saturation and cannot show the range of saltation likely occurring between sites with 100% cover. This limits possible interpretations from the upper section of Figure 5b. Notably, the bare interdune (Q2-2(1)) maintains 100% ripple cover with a lower surface SR than most sites (-63%). Notwithstanding this phenomenon, sites which were previously vegetated experienced SR up to 40% without significant sand movement.

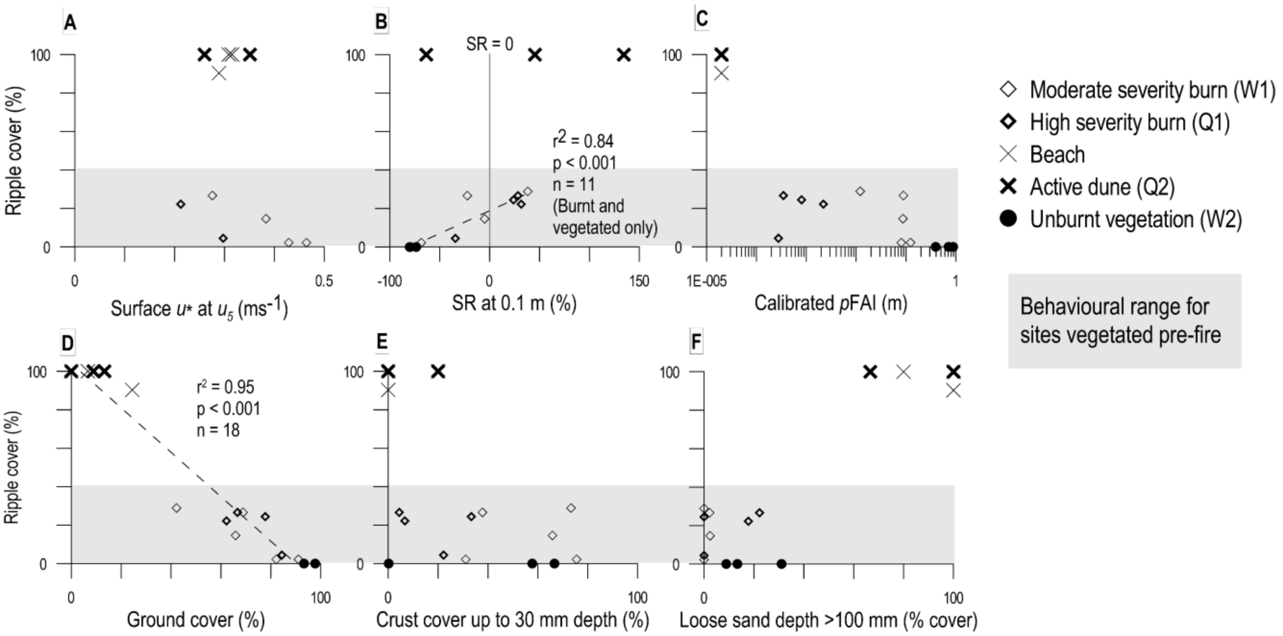

Figure 5: Wind parameters and ground survey variables plotted against percentage cover by aeolian ripple feature. (A) Surface u_* at u_5 (i.e. u_* when u_h = 5 ms^{-1}) taken from log-linear profiles; (B) Speed-up Ratio (SR) measured at 0.1 m above ground; (C) upwind calibrated pseudo Frontal Area Index (*p*FAI); (D) Percentage ground points covered by vegetation or litter (ground cover values do not include above ground canopy); (E) Percentage crust cover up to and including 30 mm below ground; (F) Percentage ground covered by loose sand of greater than 100 mm depth. Shading highlights the behavioural range in terms of ripple cover (y-axis) for all sites which were vegetated prior to the fires.

Figure 5c-f explores other possible controls on aeolian activity from our survey. Our calibrated measure of *p*FAI shows no correlation with ripples (Fig. 5c). Within this relationship, ripple cover increases significantly with ground cover below 40% (Fig. 5c). There is a strong correlation (r^2 = 0.95) between ripple cover and ground cover (Fig. 5d) but no such relationship when considering only crust cover (up to 30mm burial depth) (Fig. 5e). A large range of crust cover occurs across all previously vegetated sites and it does not explain the distribution of ripple cover (Fig. 5e). A more comprehensive measure of the available loose sand (percent area >100 mm depth) shows a clearer distinction between bare and not-bare, potentially providing some explanation (Fig. 5f). However, there is no clear relationship within the lower cluster (Fig. 5f).

3.3.4 Burn severity and short term recovery

NDVI values showed a substantial drop after both fires due to reduction of green biomass. Quallilup Beach does not show a strong recovery within the study period. Three points Q1-2(1, 2 and 4) reached 50-60% of pre-fire values around six months post-fire (Fig. 6b). The dune slope Q1-2(3) reached 73% in the same time period but had relatively low pre-fire values (Fig.6b). All points had a consistently low biomass irrespective of their pre-fire state (Fig. 6a). Recovery at Wylie 1 was more varied, with inland sites W1-2(4 to 5) showing NDVI values ≤ 78% of pre-fire values within the study period. Other points in the interdune W1-2(2 to 3) showed poor recovery,

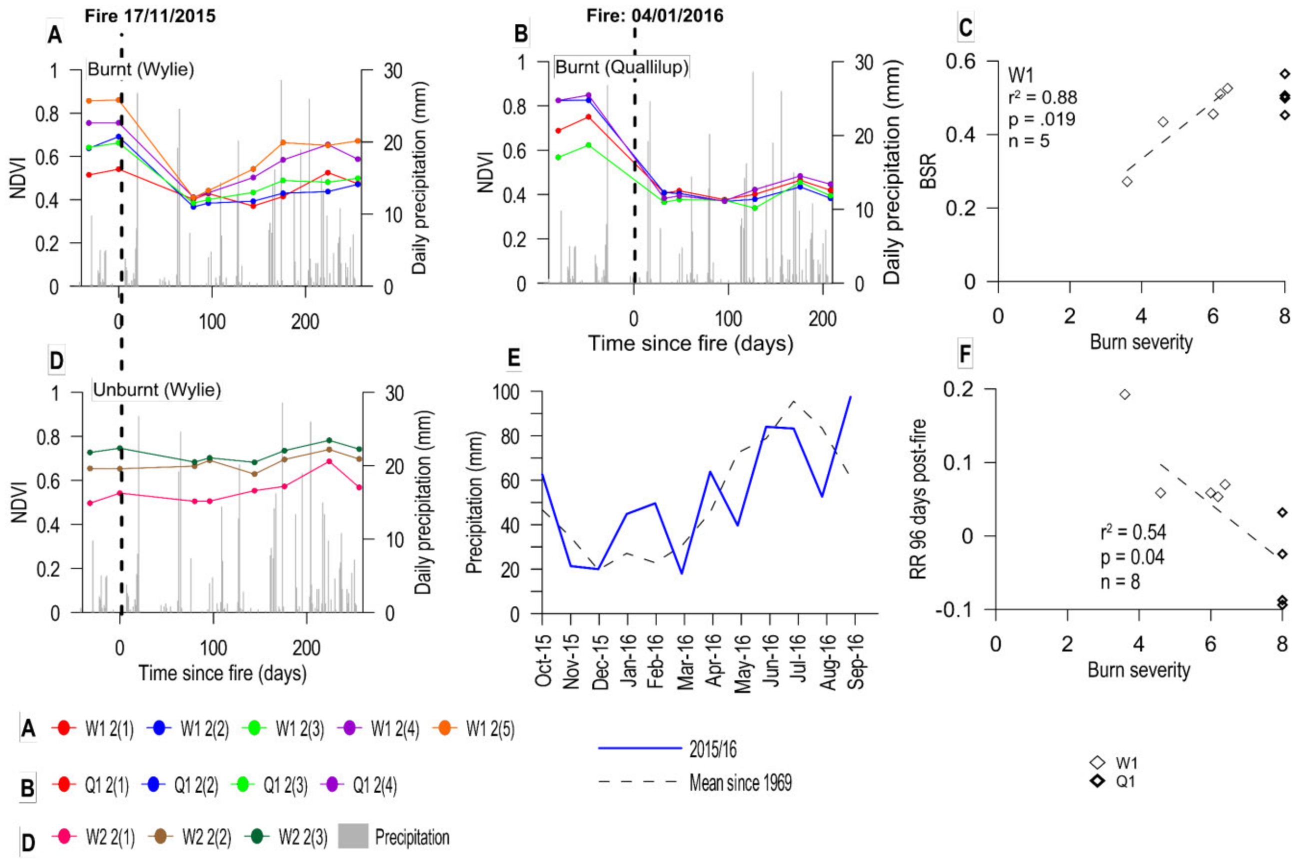

Figure 6: Results of NDVI monitoring. (A, B & D) NDVI and daily precipitation recorded in Esperance plotted with time since fire for the period up to 8 months post-fire. Relevant fires are marked and labelled at x = 0. Time since fire for A & D corresponds to the Wylie Bay fire on 17/11/2015. Time since fire for B corresponds to the Quallilup Beach fire on 04/01/2016. (E) Monthly precipitation plotted for the study period with average monthly values since 1969. Precipitation data obtained from Australian Bureau of Meteorology (www.bom.gov.au/climate/data/). (C & F) Results of burn severity assessment and relation to recovery patterns. (C) Field observations of burn severity averaged for each burnt survey location plotted against corresponding burn severity ratios (BSR). Linear regression is shown only for survey locations at site W1. (F) Recovery Ratio (RR) at 96 days (~3 months) post-fire for all burnt sites plotted against measured burn severity. Linear regression is shown for all sites except W1-2(1) (RR ≈ 0.2), where only part of the foredune was burnt and the RR (extracted from a 30 m Landsat pixel) expresses a dual dynamic of recovering plants with adjacent healthy communities.

similar to Quallilup. Both locations on the Wylie Bay foredune (W1-2(1) and W2-2(1)) had low NDVI values pre-fire (0.5 to 0.6) when compared with other Wylie locations (0.6 to 0.9) (Fig. 6 a; d). This may result from the partial coverage of the beach within the 30 m Landsat pixel, or from a different vegetation structure. During January, February, and April, Esperance received above-average rainfall (Fig. 6e). Within three weeks of both fires, Esperance had received >40 mm rain, likely allowing for the small amount of recovery seen 90 days post-fire at Wylie 1 (Fig. 7). The same recovery was not observed at Quallilup 2 (Fig. 7). A steep rise in NDVI between 9 April 2016 and 11 May 2016 might relate to 86 mm of rainfall between the dates (Fig. 6a; b; d). However, 118 mm fell before the next measurement and the same response is not consistently seen (Fig. 6a; b; d).

For site W1, observed burn severity matches well with BSR values (R^2 = 0.88) (Fig. 6c). For site Q1, there was some variation in BSR while the on-site assessment showed a consistently high level of severity (eight for all locations) so a relationship is not seen. Despite variations in on-ground burn severity, all sites had post-fire NDVI values ~0.4 (Fig. 6). Site observed burn severity has only a moderate relationship (R^2 = 0.54) with short-term recovery (represented by RR values 96 days post-fire) (Fig. 6f). This relationship excludes the foredune at Wylie

1 [W1-2(1)] (shown at burn severity = 3.6) because it was not completely burnt. A range of RR is seen at Quallilup 1 (which was uniformly recorded at eight on the burn severity scale), however, only one RR value is above zero. At Wylie 1 all locations have similar RR, despite a range of burn severity (Fig. 6f). In contrast to the consistent RR across locations at Wylie 1, repeat on-ground photos reveal generally slower recovery on the hummocky interdune area than nearby dune crests (Fig. 7). Stabilised parabolic dunes [W1-2(4-5)] showed some re-sprouting in February 2016, becoming a dense cover of *Acacia cyclops* saplings by June 2016 (Fig. 7). Quallilup 1 showed no recovery in February 2016 (Fig. 7). By June 2016 there were some small clumps of re-sprouting sedges, herbs, small shrubs and creepers e.g. *Lepidosperma*, *Nitraria*, *Scenecio* (Fig. 7). The species found on nearby unburnt dunes such as *Acacia* and *Scaevola* were not represented within this regrowth.

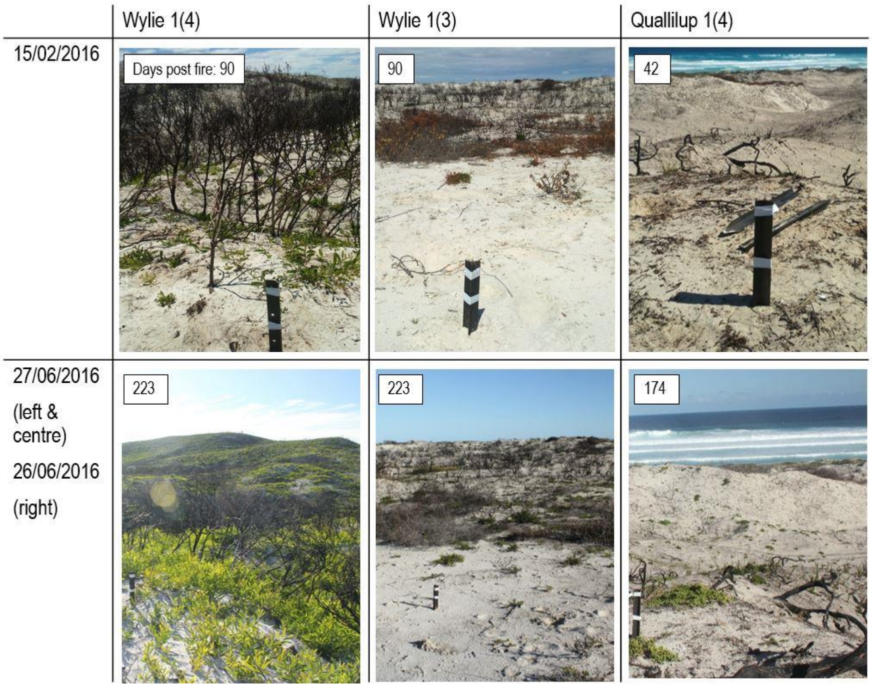

Figure 7: Images from Wylie Bay dunes showing recovery at three months (top) and seven months (bottom) post-fire and Quallilup Beach dunes showing recovery at one month (left) and five months (right) post-fire. Reference markers can be seen in each image with heights of ~20 cm. Slight differences in camera angle and scope occurred between visits. The green biomass in the top left-hand image is dominantly *Acacia cyclops* with some *Leucopogon sp.* It is expected the follow-up image (bottom left) comprises similar species.

3.4 Discussion

3.4.1 Limitations of the survey method

We acknowledge several limitations to the approach used here. Hesse and Simpson (2006) found point surveys to over-predict estimated projected cover when compared with a line-intercept method. Nevertheless, they recorded strong correlation between the methods (Hesse and Simpson, 2006). We therefore acknowledge that our survey data are best suited as site-specific relative measures. Moreover, while the aim of our wind readings is to analyse the difference between roughness effects of burnt vegetation and that of bare and unburnt surfaces, topography has a significant influence on wind (Gares and Nordstrom, 1995; Fraser et al., 1998; Finnigan, 2007; Levin et al., 2008; Hugenholtz and Wolfe, 2009; Smyth et al., 2012). Topography affects velocity, the shape of the wind profile, and complex turbulent flow within canopies (Finnigan, 2007; Walker et al., 2009; Bauer et al., 2012; Chapman et al., 2013). The absence of detailed modelling of topography and high resolution wind velocity readings in three dimensions presents a challenge for isolating the effect of burning on wind profiles. A particular concern for us is the difference in elevation between measurement locations on dunes at Wylie (≤15 m) and Quallilup (≤60 m) (Fig. 3). Furthermore, several additional relevant variables were excluded, such as: subtle variations in wind direction affecting fetch length (Lancaster and Baas 1998); plant porosity and flexibility (Wolfe and Nickling, 1993); and the related effects of gusts and variable wind speed on effective protection (e.g. bending vegetation to create a streamlined surface and skimming flow) (Wolfe and Nickling, 1993; Hesp, 2002).

3.4.2 Wind flow through burnt vegetation

Our data show no relationship between near-surface u_* and roughness element density (Fig. 4). This contrasts with other authors' observations of above canopy friction between bare, vegetated, and burnt sites (Wiggs et al., 1994; Lancaster and Baas, 1998; Whicker et al., 2002). Studies on vegetated sites often measure the velocity profile on top of the vegetation (Wiggs et al., 1994; Gares and Nordstrom, 1995; Lancaster et al., 1996). This is effective in comparing the drag effect of vegetation on regional winds, but neglects the measurement of critical sand-moving wind at the surface (Frank and Kocurek, 1996; Wolfe and Nickling, 1996). We chose near-surface measures because of their primary role in moving sand (Frank and Kocurek, 1996). Without three dimensional anemometry we could not accurately estimate u_* within dense vegetation (site W2). In their absence we cannot identify how burnt sites differ from vegetated regarding u_*. Furthermore, the poor correlation between u_* and *p*FAI does not improve when calibrated to include the porosity of burnt vegetation (Fig. 4b; c). While it is likely that other field methods used for deriving roughness density (e.g. Lancaster and Baas, 1998) have been more effective than our point intercept method, our results support Hesse and Simpson's (2006) observations that measurements based on silhouette area are less appropriate for complex vegetation cover. The observed vegetation has numerous species representing numerous plant functional groups (such as grass, forbs, shrubs and trees) with a range of geometries (such as width/height) and size (silhouette area).

While estimates of u_* are unavailable for Wylie 2, inferences can be made from the wind profile shapes and near-surface SR values (Fig. 3; 4). The below-canopy deceleration at Wylie 2 is consistent with the general understanding of friction produced by vegetation (Wolfe and Nickling, 1993). By comparison, burnt vegetation locally enables near-surface winds to flow more like wind moving over bare surfaces than vegetated, without a roughness-related disruption of the lower profile (Fig. 3). Wiggs et al. (1994) recorded a 200% increase in winds at 0.5 m from unburnt to burnt vegetation in the Kalahari Desert. Our results generally support this observation. However, remnant burnt vegetation retains some along-transect decelerating effect on surface wind (Fig. 3). This is clearer once we account for topographic sheltering [also found by Wiggs et al. (1996)] (Fig. 4). Our data suggests that burnt ground cover collectively generates friction with onshore winds and restricts near-surface wind velocity. This effect is proportional to the level of remaining ground cover (r^2 = 0.8) (Fig. 4d). However, this analysis does not consider the effect of plant structure, or the total elevation of each location. Additional above-canopy measurements may enable a better assessment of the boundary shear created by burnt and unburnt vegetation. Furthermore, a better comparison may result from pre- and post-fire measurements.

3.4.3 Dynamics of post-fire aeolian activity

The results for ripple cover can be summarised as two general surface behaviours; sites vegetated pre-fire, and sites previously bare (Fig. 5). In this environment, ripple cover is more influenced by the availability of wind energy (SR) than by the character of wind-flow at any given wind speed (u_*) (Fig. 5). Increased FAI has been shown to decrease sediment flux (Lancaster and Baas, 1998; Kuriyama et al., 2005). This relationship is not seen in this study, likely because of the oversimplified measurement of *p*FAI (calibrated or not) and the natural complexity of surface vegetation cover. Importantly, there is an overall increase in ripple cover from unburnt to burnt vegetation (0 to 30%) (Fig. 5), consistent with results from similar studies (Wiggs et al., 1994; Miller et al., 2012). However, burnt surfaces have significantly lower ripple cover than previously bare locations (90 to 100%) (Fig, 5). On typical bare or partially vegetated dune surfaces, saltation increases toward dune crests owing to wind acceleration up-slope (Wiggs et al., 1994; Frank and Kocurek, 1996). This phenomenon was seen during field work at Quallilup 2 where saltation rates appeared higher at the dune crest, but the limitation of ripples as an index for aeolian activity means our data does not show this variation. Where ripple cover is lower (below the saturation point for ripple cover) at Quallilup 1, ripples are more abundant on the slope and crest than the preceding interdune, reflecting the increased SR moving up the slope (Fig. 3c). This suggests some similarity of behaviour between bare and burnt where woody structures have been significantly reduced. However, SR values are still lower at Quallilup 1 than the slope and crest at Quallilup 2 (perhaps due to difference in overall elevation), and ripple cover does not match that of previously bare surfaces (Fig. 5). At Wylie, dune crests have fewer ripples than interdunes, indicating a break-down of this trend, perhaps in part because of re-sprouting plants (Fig. 7). At both bare sites we infer that ground cover is acting to both protect the surface, and slow the wind. The break-down of topographic wind acceleration is more significant for the moderately burnt Wylie 1.

There appears to be a complex interaction between ground cover, vegetation, wind and sand movement. Considering only wind, previously-vegetated locations experience SR of up to 40% without substantial erosion (Fig. 5b). However, the occurrence of 100% ripple cover on the sheltered interdune surface at Quallilup 2 with low SR (-63%) accentuates the separate behaviours of previously-vegetated and previously-bare, and suggests aeolian activity is not solely influenced by direct exposure to onshore winds. Overall there is a correlation between ground cover, which includes vegetated and other litter cover, and sand movement ($r^2 = 0.95$) (Fig. 5d). Within this relationship, a threshold cover of 40% was found, below-which ripple cover significantly increased (Fig. 5d). Other studies have produced site-specific or wind tunnel threshold covers typically around 15% cover (Buckley, 1987; Wiggs et al., 1995; Lancaster and Baas, 1998; Kuriyama et al., 2005). The possible threshold of 40% seen here is similar to Wolfe and Nickling's (1993) suggestion of 40% cover being adequate for total protection, though we do not suggest the same skimming flow is occurring here. Despite the observed influence of crust cover on aeolian activity on Australian desert dunes (e.g. Hesse and Simpson, 2006; Levin et al., 2012), in this study, the percentage of near-surface crusting does not explain ripple cover, likely because such large variation of crust cover occurs on non-bare sites (Fig. 5e). When we take the percentage of surface covered by significant amounts of loose sand (>100 mm), which indicates sediment availability and the inverse of surface soil cohesion, there is a possible relationship with ripple cover. However this is compromised by extreme data clustering and, unlike ground cover, within the cluster of previously vegetated sites there is no correlation. This is partly because dense vegetation was sometimes protecting the unconsolidated sand from ripple formation despite the absence of cohesion (Fig. 5e). Therefore, without ruling out soil cohesion as a contributing factor, we take ground cover to be most influential in limiting sand transport (Fig. 5). In general, our data suggests ground cover simultaneously affects the availability of sediment for transport, and wind speed, which together influence aeolian activity within the constraints of topographic and surface characteristics.

The restriction of sand transport due to ground cover (and/or soil cohesion) and wind deceleration has implications for potential de-stabilisation of dunes post-fire. Active dunes in temperate environments require sufficient sediment movement to bury plants, expose roots, and erode seedlings in order to perpetuate the bare surface (Yizhaq et al., 2013). The threshold of sand movement at which bare ground is likely to persist is unknown. Vermeire et al. (2005) recorded 2 to 48 times as much sediment movement on dunes post fire. Yet despite heavy grazing and harsh conditions for plant growth, no blowouts developed (Vermeire et al., 2005).

3.4.4 Burn severity and recovery

Typically, fires produce only a temporary reduction in vegetation cover (Ravi et al., 2012). Ravi et al. (2012) and Stout (2012) found post-fire vegetation in grasslands to recover within six months, similar to the resprouting ground cover found at W1. In both of their cases, aeolian activity was reduced 3-4 months post-fire (Ravi et al., 2012; Stout, 2012). Studies in desert and forested regions have shown much longer periods of recovery (e.g. >3 years) before reaching threshold vegetation cover (Whicker et al., 2006; Levin et al., 2012). In contrast, shrub species in Australia's Mediterranean climate regions typically establish seedlings soon after fires (Keeley, 1995).

Generally, the photographs and NDVI monitoring show the recovery at Quallilup Beach is significantly less than at Wylie Bay (which experienced a less severe burn) (Fig. 7). The complex recovery pattern at Wylie (Fig. 6a; 7) highlights the importance of seedbank and distribution of key species in regeneration. Observations of recovery in Western Australian heath suggest post-fire recovery is dominated by obligate seeding species, with lower recruitment seen in facultative resprouting species (Bell, 2001). This pattern is consistent with results from coastal dunes elsewhere [e.g. New South Wales (Benwell, 1998)] and is particularly true of the south coast of WA where reseeding plants can comprise up to 50% of species (Bell and Loneragan, 1985; Bell, 2001; Hassell, 2001). At Wylie Bay, *Acacia cylcops*, which reproduces from hard-cased seeds, shows good regeneration and is widely distributed among the dune slopes and crests (Fig. 7). Wind measurements show slopes and crests are most susceptible to strong winds (Fig. 3), thus, the distribution of fast-recovering species here is likely an important dynamic for de-stabilisation potential.

NDVI values have been observed to respond to rainfall patterns spatially and temporally (Wang et al., 2001; Wang et al., 2003). While monitoring desert dune vegetation recovery from fires, Levin et al. (2012) observed a strong correlation between NDVI and cumulative rainfall after 5.5 months. This study is concerned not with seasonal response but with initial recovery of ground cover which requires precipitation, particularly for reseeding species (Keeley, 1995). A delay in post-fire seedling recruitment up to ~5 months after below-average rainfall has been observed in dry coastal heath on dunes elsewhere in Australia (Benwell, 1998). On a regional scale, Shumack and Hesse [in prep. (Chapter 2)] found a weak ($r^2 = 0.29$) but significant relationship between total rainfall three months post-fire and recovery ratios up to nine months in the Esperance region. At the local scale, a precipitation-related difference in recovery could not be identified because precipitation records from Esperance show ample rainfall occurring post-fire to encourage regrowth, with above-average rainfall four out of six months post-fire (Fig. 6e). Except for a possible response in NDVI to high rainfall in April, rainfall patterns are not uniformly reflected by recovery. Rather, we see high within- and across-site variability (Fig. 6).

Burn severity does not show a linear correlation with RR after 96 days (Fig. 6f). However, Wylie 1 had a consistently higher RR than Quallilup 1, where recovery had apparently not begun, and also had a lower burn severity (Fig. 6f). The difference in burn severity is better characterised by on-ground observations (representing differences in remnant vegetation structure) than BSR (representing differences in overall photosynthetic biomass). At Wylie 1, there is a consistent RR across sites despite a variety of burn severity (and BSR) values, and a range of NDVI recovery patterns (Fig. 6a; f). This is consistent with the findings of Shumack and Hesse [in prep. (Chapter 2)], who record that regionally, BSR shows no correlation with RR. At Quallilup 1, however, where burn severity was deemed extreme, there is a contrasting recovery pattern to that of Wylie 1 (Fig. 6f). Burn severity (or burn intensity) at Quallilup has possibly inhibited the capacity of resprouters and reseeders to regenerate (Wright and Clarke, 2007). The few recovering plants seen in photos at Quallilup 1 six months post-fire do not resemble the community of plants seen on nearby unburnt dunes (Table 2) (Fig. 7). This likely represents one of two scenarios: either the pre-existing community at our survey site was not dominated by the same species as other dunes at Quallilup Beach and Wylie Bay, and is not likely to recover in a similar fashion; or the regeneration of dominant species has been impeded by burn intensity, and less common species with unique adaptations are left to colonise the surface. The implications are that pre-existing species distribution is important for short-term recovery pattern, and that there could be an extreme burn intensity threshold above which recovery is impeded. Such extreme fires might not have been common during the three decades of fires on the Western Australian coast monitored by Shumack and Hesse [in prep. (Chapter 2)]. Nevertheless, despite the slower recovery, photos at Quallilup Beach six months post-fire show no blowout formation.

3.4.5 Scenarios of fire disturbance

The post-fire surface stability observed within six to seven months of fires (Fig. 7) raises questions about what conditions would be necessary for post-fire de-stabilisation. Stockton (1982) described post-fire de-stabilisation of coastal dunes in Tasmania, specifically mentioning the burning of the foredune. In that case, fires were not the only disturbance, as grazing usually followed the use of fire for clearing (Stockton, 1982). Nevertheless, one scenario for generating sufficient sand movement to initiate de-stabilisation could be a burnt foredune. This may increase onshore wind acceleration over the dune, with the beach providing an abundance of upwind loose sediment supply and fetch length (Wiggs et al., 1994; Arens et al., 2004; Bauer et al., 2009; Chapman et al., 2013; Hesp, 2013). At our study sites, however, neither foredune was completely burnt despite offshore winds having apparently driven the fires towards the coast. A possibility is that the foredune vegetation (e.g. *Spinifex* and the invasive *Euphorbia paralias*) is less flammable than the heath vegetation and did not carry the fire.

The commonality of foredune de-stabilisation under natural circumstances in temperate and subhumid settings (Hesp, 2002; Hesp, 2013) may provide insights into the kind of mechanism necessary for de-stabilisation of features beyond the foredune. Hesp (2002) describes possible processes leading to foredune de-stabilisation as being the funnelling and acceleration of wind through weak spots in vegetation cover, or through concave storm scarping. Thus, a potentially important process is structural variations (topographic- or plant-related) interacting with unobstructed onshore winds to enhance localised erosion, leading to blowout development. In this study, as well as the lack of burnt foredune, the characteristics of the post-fire environment beyond the foredune do not encourage this process. Firstly, our wind measurements suggest burnt vegetation does not enhance turbulent flow (Fig. 4), rather, the uniformity of disturbance enables relatively stable flow. And secondly, there is no strong acceleration of near-surface wind when compared to onshore winds (Fig. 3).

The results presented here show that specific fire dynamics enable recovery at different rates. It is possible that severely burnt sites, such as Quallilup, with slower vegetation recovery, allow prolonged wind exposure and increased surface change. However, dune crests at Wylie Bay have abundant cover regenerating and appear unlikely to destabilise (Fig. 8). The interdune surfaces surveyed do not show the same recovery but, with the exception of one partially-bare location at the dune toe [W1-2(3)], are generally less exposed to strong onshore winds (Fig.3a). The outcome at Quallilup Beach remains unknown. Small patches of green (Fig. 8) observed six months post-fire may be the beginning of a delayed regeneration. Shumack and Hesse [in prep. Chapter 2)] found that even areas of coastal dunes in WA with delayed regrowth up to six months due to lack of early rainfall or species distribution saw eventual recovery. Alternatively, the fire-related heat may have caused sufficient damage to the seedbank to inhibit long term regeneration (Nieuwenhuis, 1987; Keeley, 1995). In this scenario, eventual blowout development will depend on the balance between available sediment, sufficiently erosive wind-flow, remnant protective cover, sediment cohesion, and the ability of colonising species to establish themselves (van Dijk et al., 1999; Hesp, 2002; Barchyn and Hugenholtz, 2013). A key finding is that ground cover and sediment availability are acting to protect the surface after fires (Fig. 6). Even with a delayed recovery, a second disturbance which further reduces surface protection and cohesion could be necessary for de-stabilisation.

3.5 Conclusions

Our aim was to establish the nature of disturbance to coastal dunes from fires by exploring relationships between wind, vegetation, surface properties and sand movement on recently burnt dunes. Locally, burnt vegetation enables near surface winds to flow with a similar profile shape to bare surfaces (e.g. beach). There is also an observed increase in speed-up ratios of between 5 and 120% from vegetated to burnt surfaces. However, as a surface, burnt ground cover may still generate friction and restrict acceleration of near-surface wind. Increase in erosion and surface sand movement after fires is evident (≤ 30%). The key issue is whether this is sufficient to de-stabilise the dune. Our results suggest that during the period immediately post-fire, damage to dune protective covering and resultant aeolian activity does not threaten eventual de-stabilisation. Despite the increase in ripple cover post-fire, values are significantly less than measures of aeolian activity on previously bare surfaces (by 60 to 100%). This is most obviously due to ground cover ($r^2 = 0.95$), which protects the surface and may reduce wind availability. However, surface cohesion and the limited availability of loose sand is also a defining characteristic of previously vegetated surfaces when contrasted with beaches and bare dunes. The two sites investigated experienced different fire severities and showed somewhat different recovery pathways. One fire with moderate severity (Wylie Bay) allowed for substantial seedling recruitment on dune crests within six months post-fire. The other fire (Quallilup Beach) burnt with a high to extreme severity and no significant vegetation recovery was recorded within the study period, possibly due to the death of stored seeds and buds. The outcome at this site is unclear. Implications are that fire as the sole disturbance is not apparently a major threat to the stability of coastal dunes, with the possible exception of a threshold for burn severity, beyond-which ground cover re-establishment is inhibited and the dune becomes susceptible to further disturbance.

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3.7 References

(See combined reference list at the end of the thesis)

Chapter 4 – Conclusion

4.1 Synthesis of key findings

This thesis has addressed the hypothesis that fire plays a role in destabilising coastal dunes. This has been investigated using fires occurring on Western Australian (WA) coastal dunefields as a case study. Within this setting, two distinct approaches have been used. Firstly, Chapter 2 addressed the hypothesis on a regional scale, analysing dune surface responses to multiple fires over the medium-to-long term in recent decades. Secondly, Chapter 3 addressed the hypothesis on a local scale, investigating the post-fire surface disturbance on dunes near Esperance, WA, which had been burnt one to three months prior to fieldwork.

Fires burning between 1988 and 2007 in southwest WA were found not to contribute to the initiation of blowout features. A consistent pattern of vegetation recovery was observed, most notably with a rapid re-establishment of ground cover within nine months, followed by a steady recovery of photosynthetic biomass signal up to seven years (Aim i). Some variation in the first nine months is explained by precipitation rates with lower rainfall allowing less early regrowth (Aim ii). This relationship thereafter diminishes and the key determinant on post-fire ground cover is the pre-fire cover or seedbank distribution (Aim ii). This is supported by the image classifications which revealed no additional areas of bare sand where fire was determined as the initiating disturbance (Aim iii).

The results shown in Chapter 3 provide insight into the outcomes of the regional analysis. A key finding is that fires did not enhance aeolian activity to levels seen on active dunes (Aim vi). Burnt vegetation allowed wind to flow with relative stability, not imparting the same roughness effects as dense unburnt vegetation (Aim v). However, there was still some along-transect reduction of topographic acceleration when burnt surfaces were compared with wind-flow up a bare stoss slope (Aim v). This effect appears to be related to overall ground cover (Aim vi). Aeolian activity generally increased from vegetated to burnt, but is only one third of the amount seen on previously-bare surfaces (Aim vi). This proportion is likely even smaller as 100% ripple cover represents a saturation point and may not express the actual difference in saltation rates. Aeolian activity is restricted by ground cover, wind deceleration, and possibly by soil cohesion (Aim vi). Analysis of local recovery patterns supports the findings of Chapter 2, where species distribution was a key determinant (Aim vii). However, the possible inhibition of short term recovery from extreme fire intensity contrasts with negative results from the regional-scale assessment shown in Chapter 2 (Aim vii).

The broader implications are that fires as disturbances are, by themselves, not currently a major threat to the stability of coastal dunes, with the possible exception of a threshold for burn severity, beyond-which ground cover re-establishment is inhibited. These results do not negate the process of post-fire de-stabilisation interpreted elsewhere from dune stratigraphy in sub-arctic and desert dunes (Filion, 1984; 1987; Filion et al., 1991; Seppala, 1995; Kayhko et al., 1999; Mann et al., 2002; Carcaillet et al., 2006; Lomax et al., 2011; Matthews and Seppala, 2014), and on the Lithuanian coast (Gaigalas and Padzur, 2008). However, the propensity for temperate and sub-humid coastal heath vegetation to rapidly re-establish effective surface protection highlights the need for extreme conditions or additional disturbance to initiate active dune formation following wildfires.

4.2 Directions for future research

Several additional methods would enhance our understanding of the subject, and could be used to address the limitations of the studies discussed within each chapter. Firstly, a study of fires confined to the period of Landsat Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) coverage would enable pan-sharpening of images to ~15 m resolution. Alternatively, multi-temporal high resolution aerial imagery would enable a more detailed monitoring of bare sand area and vegetation response to fire. If these are unattainable, the trial of within-pixel indices of ground cover (e.g. BI or fractional cover), or a change detection algorithm may be more appropriate than the coarse resolution classification used here. For the local-scale assessment of disturbance from fires, measurements of wind, vegetation, and saltation could be improved. Three-dimensional anemometry used above- and within-canopy would supplement horizontal velocity measurements with accurate estimates of turbulence (i.e. friction) generated by burnt and un-burnt vegetation. One way to normalise for the effects of topographic sheltering could be to opportunistically obtain readings from the same location before and after a fire. More accurate estimates of plant cover effective for interacting with wind, including porosity, could be explored with a terrestrial laser scanner. And finally, accurate observations of saltation taken simultaneously on burnt, unburnt, and bare surfaces would account for the saturation point of ripple cover.

Beyond the scope of this study, several topics related to the post-fire de-stabilisation of coastal dunes require further attention. Despite the general trend of post-fire recovery and stability seen on coastal dunes in WA, there are several situations where fires may still play a role in active dune formation. As surface protection and soil cohesion appear to limit post-fire surface erodibility and the availability of sediment, the most likely scenario for post-fire de-stabilisation is where additional local disturbance occurs, such as grazing. A detailed case study where fires have compounded with other disturbances would provide insight here. In this case, fire might act to enhance wind-flow to an already disturbed and eroding surface (e.g. cleared for land use). Alternatively, we speculate that where foredunes are burnt (not seen in this study) the beach would provide an upwind sediment source, and remnant woody structures of smaller foredune shrubs would provide minimal roughness. This may provide the necessary conditions for active dune development. The actual likelihood of fires burning on foredunes is unknown. Another possible scenario for dune de-stabilisation is when extremely intense fires inhibit regeneration, allowing prolonged exposure to winds and susceptibility to further disturbance. A similar effect might result from a changing regional climate (e.g. drought conditions), or fire regime (e.g. more frequent fires). Each of these scenarios is worthy of further investigation. While this thesis has investigated the role of fires in West Australian coastal dune geomorphology, the exploration of site- and region-specific dynamics between fire and dune erosion for other coastlines and climate regions would give a more comprehensive picture.

Chapter 5 – References

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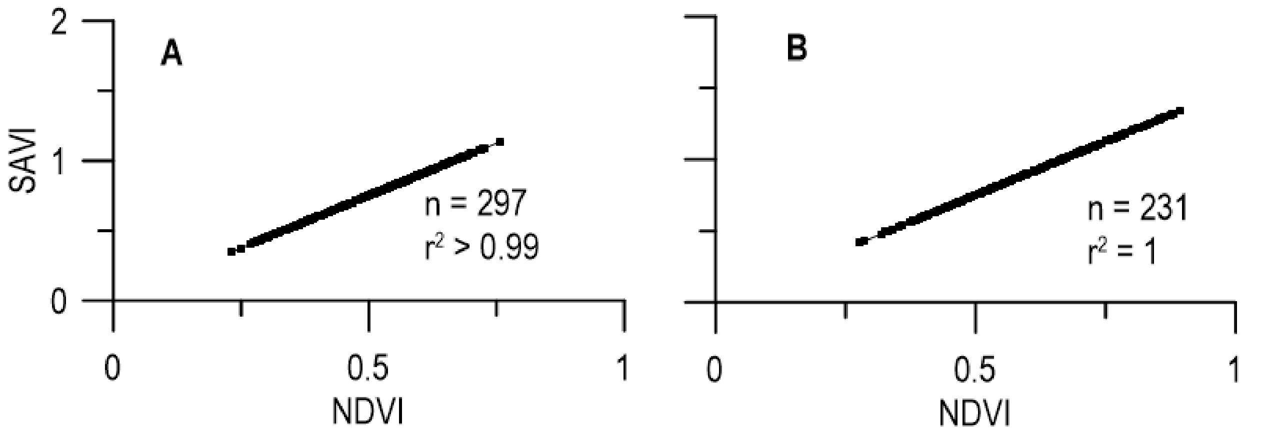
Chapter 6 – Appendices

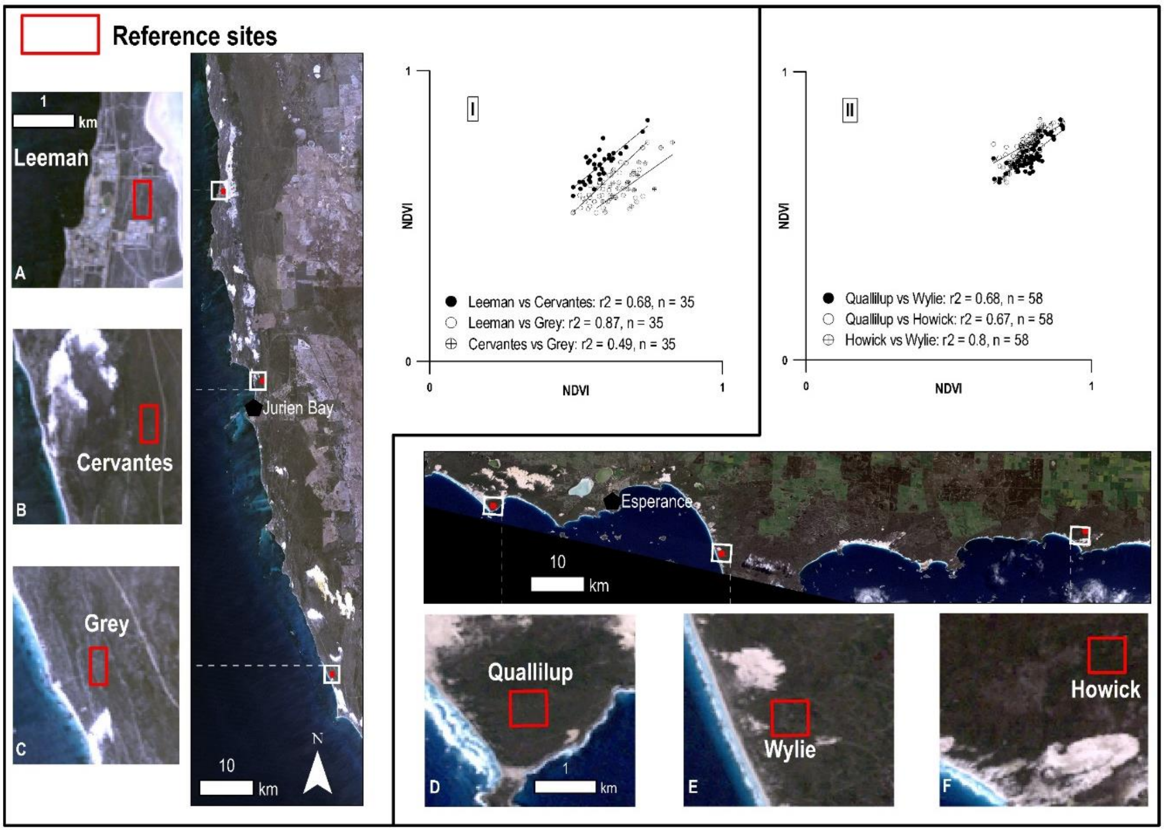
Appendix 1. List of Landsat images processed and analysed for Chapter 2

West coast				South coast			
Sensor	**Capture date**	**Path**	**Row**	**Sensor**	**Capture date**	**Path**	**Row**
Landsat 5 TM	11/12/1988	113	81	Landsat 5 TM	8/02/1988	108	83
Landsat 5 TM	12/01/1989	113	81	Landsat 5 TM	12/04/1988	108	83
Landsat 5 TM	28/01/1989	113	81	Landsat 5 TM	30/05/1988	108	83
Landsat 5 TM	13/02/1989	113	81	Landsat 5 TM	1/07/1988	108	83
Landsat 5 TM	17/03/1989	113	81	Landsat 5 TM	17/07/1988	108	83
Landsat 5 TM	21/06/1989	113	81	Landsat 5 TM	22/11/1988	108	83
Landsat 5 TM	8/08/1989	113	81	Landsat 5 TM	8/12/1988	108	83
Landsat 5 TM	25/09/1989	113	81	Landsat 5 TM	27/12/1989	108	83
Landsat 5 TM	14/12/1989	113	81	Landsat 5 TM	25/09/1990	108	83
Landsat 5 TM	17/12/1990	113	81	Landsat 5 TM	16/02/1991	108	83
Landsat 5 TM	17/10/1991	113	81	Landsat 5 TM	5/04/1991	108	83
Landsat 5 TM	20/12/1991	113	81	Landsat 5 TM	17/12/1991	108	83
Landsat 5 TM	22/02/1992	113	81	Landsat 5 TM	20/11/1993	108	83
Landsat 5 TM	12/05/1992	113	81	Landsat 5 TM	29/04/1994	108	83
Landsat 5 TM	15/07/1992	113	81	Landsat 5 TM	31/05/1994	108	83
Landsat 5 TM	31/07/1992	113	81	Landsat 5 TM	16/06/1994	108	83
Landsat 5 TM	19/10/1992	113	81	Landsat 5 TM	3/08/1994	108	83
Landsat 5 TM	7/01/1993	113	81	Landsat 5 TM	20/09/1994	108	83
Landsat 5 TM	24/02/1993	113	81	Landsat 5 TM	22/10/1994	108	83
Landsat 5 TM	13/04/1993	113	81	Landsat 5 TM	7/11/1994	108	83
Landsat 5 TM	31/05/1993	113	81	Landsat 5 TM	22/08/1995	108	83
Landsat 5 TM	18/07/1993	113	81	Landsat 5 TM	27/10/1996	108	83
Landsat 5 TM	19/08/1993	113	81	Landsat 5 TM	1/12/1997	108	83
Landsat 5 TM	20/09/1993	113	81	Landsat 5 TM	30/08/1998	108	83
Landsat 5 TM	23/11/1993	113	81	Landsat 5 TM	20/09/1999	108	83
Landsat 5 TM	25/12/1993	113	81	Landsat 5 TM	20/10/1999	108	83
Landsat 5 TM	28/12/1994	113	81	Landsat 7 ETM+	29/11/1999	108	83
Landsat 5 TM	18/03/1995	113	81	Landsat 7 ETM+	17/02/2000	108	83
Landsat 5 TM	19/04/1995	113	81	Landsat 7 ETM+	7/05/2000	108	83
Landsat 5 TM	10/09/1995	113	81	Landsat 7 ETM+	8/06/2000	108	83
Landsat 5 TM	16/01/1996	113	81	Landsat 7 ETM+	10/07/2000	108	83
Landsat 5 TM	1/02/1996	113	81	Landsat 7 ETM+	15/11/2000	108	83
Landsat 5 TM	17/02/1996	113	81	Landsat 7 ETM+	1/12/2000	108	83
Landsat 5 TM	20/03/1996	113	81	Landsat 7 ETM+	3/02/2001	108	83
Landsat 5 TM	21/04/1996	113	81	Landsat 7 ETM+	20/12/2001	108	83
Landsat 5 TM	23/05/1996	113	81	Landsat 7 ETM+	8/01/2003	108	83
Landsat 5 TM	10/07/1996	113	81	Landsat 5 TM	4/02/2004	108	83
Landsat 5 TM	17/12/1996	113	81	Landsat 5 TM	24/04/2004	108	83
Landsat 5 TM	1/01/1997	113	81	Landsat 5 TM	27/06/2004	108	83
Landsat 5 TM	2/01/1997	113	81	Landsat 5 TM	29/07/2004	108	83

Landsat 5 TM	23/03/1997	113	81	Landsat 5 TM	4/12/2004	108	83
Landsat 5 TM	24/04/1997	113	81	Landsat 5 TM	20/12/2004	108	83
Landsat 5 TM	5/01/1998	113	81	Landsat 5 TM	21/01/2005	108	83
Landsat 5 TM	20/10/1998	113	81	Landsat 5 TM	1/08/2005	108	83
Landsat 7 ETM+	2/12/1999	113	81	Landsat 5 TM	17/08/2005	108	83
Landsat 5 TM	26/12/1999	113	81	Landsat 5 TM	2/09/2005	108	83
Landsat 7 ETM+	19/01/2000	113	81	Landsat 5 TM	17/09/2005	108	83
Landsat 7 ETM+	23/02/2000	113	81	Landsat 5 TM	24/01/2006	108	83
Landsat 7 ETM+	8/04/2000	113	81	Landsat 5 TM	20/08/2006	108	83
Landsat 7 ETM+	24/04/2000	113	81	Landsat 5 TM	26/12/2006	108	83
Landsat 7 ETM+	16/05/2000	113	81	Landsat 5 TM	12/02/2007	108	83
Landsat 7 ETM+	14/08/2000	113	81	Landsat 5 TM	22/07/2007	108	83
Landsat 7 ETM+	1/10/2000	113	81	Landsat 5 TM	7/08/2007	108	83
Landsat 7 ETM+	17/10/2000	113	81	Landsat 5 TM	24/09/2007	108	83
Landsat 7 ETM+	4/12/2000	113	81	Landsat 5 TM	14/01/2008	108	83
Landsat 7 ETM+	5/01/2001	113	81	Landsat 5 TM	29/11/2008	108	83
Landsat 7 ETM+	23/12/2001	113	81	Landsat 5 TM	16/01/2009	108	83
Landsat 7 ETM+	10/12/2002	113	81	Landsat 5 TM	18/12/2009	108	83
Landsat 7 ETM+	27/01/2003	113	81	Landsat 5 TM	19/11/2010	108	83
Landsat 7 ETM+	28/02/2003	113	81	Landsat 5 TM	3/09/2011	108	83
Landsat 7 ETM+	3/05/2003	113	81	Landsat 8 OLI	22/07/2013	108	83
Landsat 5 TM	11/05/2003	113	81	Landsat 8 OLI	29/12/2013	108	83
Landsat 5 TM	27/05/2003	113	81	Landsat 8 OLI	27/09/2014	108	83
Landsat 5 TM	2/10/2003	113	81	Landsat 8 OLI	17/11/2015	108	83
Landsat 5 TM	21/12/2003	113	81	Landsat 8 OLI	11/05/2016	108	83
Landsat 5 TM	7/12/2004	113	81				
Landsat 5 TM	8/01/2005	113	81				
Landsat 5 TM	9/02/2005	113	81				
Landsat 5 TM	25/02/2005	113	81				
Landsat 5 TM	14/04/2005	113	81				
Landsat 5 TM	19/07/2005	113	81				
Landsat 5 TM	23/10/2005	113	81				
Landsat 5 TM	24/11/2005	113	81				
Landsat 5 TM	29/12/2006	113	81				
Landsat 5 TM	14/01/2007	113	81				
Landsat 5 TM	2/02/2008	113	81				
Landsat 5 TM	18/12/2008	113	81				
Landsat 5 TM	19/12/2008	113	81				
Landsat 5 TM	5/12/2009	113	81				
Landsat 5 TM	22/01/2010	113	81				
Landsat 5 TM	9/01/2011	113	81				
Landsat 5 TM	1/05/2011	113	81				
Landsat 8 OLI	7/06/2013	113	81				
Landsat 8 OLI	17/01/2014	113	81				
Landsat 8 OLI	4/01/2015	113	81				
Landsat 8 OLI	22/12/2015	113	81				



Appendix 2. Correlations between Normalised Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) measured from all fire areas on the west coast (A) and south coast (B) of Western Australia from 1988 to 2016.



Appendix 3. Left: reference sites chosen on the west coast with associated relationships (I) between corresponding NDVI values. Sites near Leeman (A) and Grey (C) are similar environments with moderately dense shrub cover on dune crests, their similarity is highlighted by an r-squared of 0.87 between NDVI readings. Site (B) near Cervantes has more dense interdune heath. Right: Reference sites (D to F) chosen on the south coast with associated NDVI relationships (II) showing strong similarities in vegetation type and temporal behaviour.

Appendix 4. Raw survey results from locations at Wylie Bay and Quallilup Beach, WA

Survey sites	Upwind pFAI (m)	Calibrated pFAI (m)	Ground cover (%)	Sand depth >100 mm (%)	Ripples (% area)
W1_1(0)	0	0	24.4	100	90.3
W1_2(1)	44.4	12.34	82.29	0	2.2
W1_2(2)	55	8.87	68.9	2.2	26.7
W1_2(3)	5.6	1.21	42.2	0	28.9
W1_2(4)	52.1	8.69	65.9	2.4	14.6
W1_2(5)	51.4	8.03	91.1	0	2.2
W2_1(0)	0	0	6.7	100	100
W2_2(1)	39.4	39.44	97.8	8.9	0
W2_2(2)	71.1	71.11	93.3	13.3	0
W2_2(3)	88.1	88.06	93.3	31.1	0
Q1_1(0)	0	0	0	80	100
Q1_2(1)	0.7	0.08	77.8	0	24.4
Q1_2(2)	0.2	0.03	84.4	0	4.4
Q1_2(3)	0.3	0.03	66.7	22.2	26.7
Q1_2(4)	1.8	0.22	62.2	17.8	22.2
Q2_2(1)	0	0	8.9	66.7	100
Q2_2(2)	0	0	13.3	100	100
Q2_2(3)	0	0	0	100	100

Appendix 5. Lab results from surface samples taken at Wylie Bay and Quallilup Beach, WA. Moisture content was estimated from sample weight loss after 24 h at 105° C. Particle size was measured on dried samples using a Malvern Mastersizer. Salt content was estimated from electrical conductivity readings on 1:5 soil-water mixtures. Organic and carbonate content were calculated from loss on ignition after 4 h at 550°C and two hours at 950°C respectively. Loss on ignition between 550° C and 950°C was multiplied by 1.36 to estimate the original weight of calcium carbonate within the sample.

Sample site	Moisture (%)	Soluble salts (%)	Organics (%)	Carbonates (%)	Mean particle size (μm)
W1_2(1)	0.36	0.20	2.40	23.77	239.95
W1_2(4)	0.29	0.20	1.33	13.98	248.95
W2_2(1)	0.30	0.16	2.16	30.04	235.79
W2_2(3)	0.49	0.25	2.69	19.54	240.40
Q1_1(0)	0.50	3.88	1.92	26.57	288.18
Q1_2(1)	0.39	0.27	1.96	21.12	283.95
Q1_2(4)	0.84	0.27	3.37	26.91	264.28
Q2_2(3)	0.14	0.16	1.30	21.73	306.06

Appendix 6. Landsat images used in monitoring vegetation recovery at Wylie Bay and Quallilup Beach, WA

Sensor	Capture date	WRS path	WRS row	Time in relation to Wylie Bay fire (days)	Time in relation to Quallilup Beach fire (days)
Landsat 8 OLI	16/10/2015	108	83	-32	-80
Landsat 8 OLI	17/11/2015	108	83	0	-48
Landsat 8 OLI	5/02/2016	108	83	80	32
Landsat 8 OLI	21/02/2016	108	83	96	48
Landsat 8 OLI	9/04/2016	108	83	144	96
Landsat 8 OLI	11/05/2016	108	83	176	128
Landsat 8 OLI	28/06/2016	108	83	224	176
Landsat 8 OLI	30/07/2016	108	83	256	208