

The impacts of recreational trail infrastructure on threatened plant communities



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Statement of originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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(Date): _____

Mark Albert Nadir Bryden Runkowski

August 2015

In loving memory of my father Campbell Bryden Ballantyne and
for my grandmother Ingeborg-Helena Runkowski who both
taught me to find wonder in the natural world.

*“Today, a new sun rises for me; everything lives, everything is
animated, everything seems to speak to me of my passion,
everything invites me to cherish it”*

Abstract

Globally, nature-based tourism and recreation is increasing. As a result there is more and more infrastructure provided to allow access to natural areas, including recreational trails used for popular activities such as mountain-biking and hiking. There are many hundreds of thousands of kilometres of trails in natural areas worldwide, but what impacts do they have on native plant communities, especially those already threatened with extinction?

The first step in addressing this question involved undertaking a global systematic quantitative literature review to assess what is known and unknown about the impacts of recreational trails on vegetation and soils. The review found that of the 59 original research papers, most assessed formal trails in well-funded protected areas often looking at local-scale compositional impacts and/or trail degradation using rather location-specific, crisis-driven approaches. There were major gaps in the literature including research: (1) on threatened plant communities, (2) on temporal effects, (3) on structural and functional impacts, (4) comparing different types of trails and (5) assessing landscape-scale impacts such as fragmentation. To start to address some of these gaps, the field work component of the thesis assessed trail impacts in three contrasting threatened plant communities in Australia where trail-based recreation is popular. The aims were to determine: (1) if recreational trails damage threatened plant communities, (2) if impacts occur at direct local, indirect local and cumulative landscape scales, (3) if trails affect compositional, structural and/or functional facets of the communities and (4) if impacts vary among different types of trails.

The first community assessed was the Windswept Feldmark in the Australian Alps. A temporal study compared the impacts of an unsurfaced trail on plant composition between 2003 and 2013. There were persistent changes in plant composition associated with the trail with some species benefitting from intermediate disturbance along trail edges while others declined including some rare endemics. I then assessed how damage from the trail to the dominant keystone shrub in the community (*Epacris gunnii*) produced a barrier effect reducing the amount of facilitative habitat the shrub provided to other plants thereby affecting community function.

The second plant community assessed was Grey Box grassy woodland in South Australia. Here I compared the relative impacts of different types of trails (bare earth, gravel and tarmac) on species composition. Bare earth trails caused more degradation to the trail surface including the loss of soil and vegetation, while hardened gravel and tarmac trails resulted in greater

changes to vegetation along the trail edges. This included changes to composition such as reductions in shrubs, herbs and bulbs and increased weed cover with edge gradients varying among the different types of trails.

In the third community I assessed the impacts of different types of trails (bare earth, grass, gravel, tarmac and concrete) on remnants of Tall Open Blackbutt forest in urban areas in Queensland. Bare earth, mostly informal trails resulted in more soil loss and cumulative loss of forest, especially where the trails were excessively wider than formal hardened trails, but hardened trails did more damage to trailside forest structure with reductions in canopy and tree density. Impacts of hardened trails were likely a result of disturbance during their construction and maintenance. When the impacts of the trails were then assessed at a landscape-scale, I found that more urbanised, smaller forest remnants with multiple entry points were highly fragmented largely as a result of informal trails used for mountain-biking.

This thesis helps address important gaps in our knowledge about recreational trail impacts. Specifically I found that recreational trails pose a range of impacts to threatened plant communities often because these communities are originally degraded by urban development and the remnants are left in close proximity to dense human populations, or their distribution is restricted to specific environmental conditions which also prove popular for visitors (e.g. mountain tops). Impacts from the trails occurred at all scales in these plant communities, from direct local-scale erosion to indirect-scale changes in plant cover through to landscape-scale fragmentation. The impacts also affected all three facets of community diversity with strong compositional, structural and functional effects. Finally, the type and severity of the impacts was highly variable among trail types.

Despite their ubiquity and importance in allowing people to visit, enjoy and learn about natural areas, recreational trails require considerably more research, understanding and management to fully mitigate their impacts, especially in communities already threatened with extinction.

Table of contents

Statement of originality	i
Abstract	iii
Table of contents.....	v
List of tables	vi
List of figures	vi
List of appendices.....	vii
Acknowledgements.....	viii
Published papers included in the thesis.....	x
Glossary	xii
References.....	xiii
Chapter 1. Introduction.....	1
1.1 Nature-based tourism and recreation	1
1.2 Recreation ecology.....	2
1.3 Recreational trail impacts	3
1.4 Recreational trails and threatened plant communities	7
1.5 Threatened plant communities and trails in Australia.....	8
1.6 Aims.....	11
1.7 Thesis structure.....	12
1.8 The threatened plant communities	16
1.9 References.....	19
Chapter 2. The impacts of trail infrastructure on vegetation and soils: current literature and future directions.....	31
Chapter 3. Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps	32
Chapter 4. Recreational trails as a source of negative impacts on the persistence of keystone species and facilitation.....	34
Chapter 5. Comparing the impacts of different types of recreational trails on vegetation: lessons for conservation and management	36
Chapter 6. Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure	68
Chapter 7. Recreational trails are an important cause of fragmentation in endangered urban forests: a case-study from Australia	70
Chapter 8. General discussion.....	72
8.1 Introduction.....	72

8.2 What is the current state of research on trail impacts on vegetation and soils?	73
8.3 Do recreational trails have impacts on threatened plant communities?	76
8.4 Do trail impacts occur at direct local, indirect local and cumulative landscape scales? ..	77
8.5 Do trail impacts affect the structure, composition and function of threatened plant communities?	80
8.6 Do impacts differ in type and severity among different types of recreational trail?	84
8.7 Research contribution to knowledge	88
8.8 Implications for the management of recreational trails	89
8.8.1 General implications for the management of recreational trails in threatened plant communities.....	89
8.8.2 Specific management implications relating to the plant communities studied in this thesis	90
8.9 Future research directions	92
8.10 Conclusions	93
8.11 References.....	94
Appendices.....	101

List of tables

Table 1.1 Outline of the three threatened plant communities studied in this thesis detailing community descriptions, dominant species and climate as well as both structural and compositional attributes.....	9
Table 8.1 Summary of the impacts of different types of recreational trails among the three threatened plant communities in Australia. A downward arrow signifies a decline in the dependent variable caused by each trail type, while an upward arrow signifies an increase in the dependent variable with the size of the arrow (large, medium or small) indicating the intensity of the impact. A dash signifies no impact.	87

List of figures

Figure 1.1 Three primary ways in which trails can affect vegetation and soils (1. construction and maintenance, 2. presence and 3. use) and the scales at which they act (A. direct local, B. indirect local and C. dispersed landscape).....	6
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Figure 1.2 Summary of the structure of the thesis assessing trail impacts in three threatened plant communities. The cells describe the main variables to be tested in each community separated into compositional, structural and functional impacts (left-hand side) and among direct local (single square), indirect local (double square) and cumulative landscape scales (multi square).....	15
Figure 1.3 Examples of the three threatened plant communities studied in this thesis. Photographs by M. Runkowski.....	18
Figure 8.1 Summary of the key results of field research chapters assessing trail impacts in three threatened plant communities. Ruler/clock symbols represent spatial/temporal studies, respectively, while single squares represent direct local scale impacts, double squares are indirect local scale impacts and multiple squares are cumulative landscape scale impacts on compositional, structural and functional biodiversity. Dashes signify no impact and multi-head arrows, multi impacts.....	75
Figure 8.2 Possible flow of works in creating more sustainable trail networks in threatened plant communities and managing for both conservation and recreational benefits.	91

List of appendices

Appendix 1 Griffith University policy for the submission of PhD theses as a series of published and unpublished papers. Available http://www.griffith.edu.au/higher-degrees-research/current-research-students/thesis/preparation/thesis-as-a-series-of-published-unpublished-papers , accessed 17 June 2015.....	101
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Published papers included in the thesis

This thesis includes published and in press papers in Chapters 2, 3, 4, 6 and 7 which are peer-reviewed and co-authored with other researchers. Also included in this thesis is a submitted paper currently under peer-review (Chapter 5) that is co-authored with other researchers. My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) for these papers including all authors, are:

Chapter 2: Ballantyne, M. and Pickering, C.M., (2015) The impacts of trail infrastructure on vegetation and soils: current literature and future directions. *Journal of Environmental Management*. **164**, 53-64.

Chapter 3: Ballantyne, M., Pickering, C.M., McDougall, K.L. and Wright, G.T., (2014) Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps. *Australian Journal of Botany* **62**, 263-275.

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Chapter 6: Ballantyne, M. and Pickering, C.M., (2015) Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure. *Journal of Environmental Management* **159**, 94-105.

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Glossary

Alpine zone: area of a mountainous ecosystem where the growing season extends for a 94 day minimum duration and the mean growing season temperature is 6.4°C (Körner et al., 2011). In Kosciuszko National Park, this lies between 1,850m - 2,228m (Costin et al., 2000).

Ecosystem: a spatially explicit and open unit of the earth that includes all of the organisms and components of the abiotic environment within its boundaries, as well as their associated interactions (Fauth, 1997).

Fragmentation: an umbrella term encompassing a wide variety of patterns and processes initiated by anthropogenic activity and resulting in the loss of vegetation and animal habitat. All the different patterns, processes and consequences of fragmentation are interrelated and often include the timing and type of clearance (e.g. linear division, braiding, blanket clearing), loss of sensitive species, creation of fragments of differing size, islandisation, habitat edges, altered species interactions and so on (Lindenmayer and Burgman, 2005; Ewers and Didham, 2007).

Formal trails: Planned and designed trails to provide recreation opportunities for visitors in areas relatively resistant to disturbance (Marion and Leung, 2011).

Graminoid: sedges, rushes and grasses combined.

Informal trails: Unhardened visitor-created trails that are often poorly designed and located and not maintained (Marion and Leung, 2011).

National Park: In Australia, this term applies to land set aside for permanent preservation of natural conditions and cultural resources/values. The use of these areas should be nature-based and ecologically sustainable (Queensland Government, 2009).

Nature-based tourism: activities that visitors take part in during a holiday whereby they engage with nature in a location away from their home environment (Newsome et al., 2013; Bell et al., 2007).

Nature-based recreation: nature-based activities that people engage in within a natural or semi-natural location as part of their leisure time (Nicholls, 2006; Bell et al., 2007).

Plant community: an integrated assemblage of plant species in which a common continuum of independent and interdependent relationships exist (Lortie et al., 2004).

Recreation ecology: the scientific study of the impacts of nature-based tourism and recreation on natural and semi-natural environments (Liddle, 1997).

Recreational trails: a thoroughfare across a terrestrial environment that is used for tourism and/or recreational purposes.

Resilience: the capacity for a plant species or community to recover following disturbance.

Resistance: the capacity of a plant species or community to withstand disturbance before being damaged.

Threatened species/ecosystem/community: any species, ecosystem or community listed as in danger of extinction (near threatened, vulnerable, endangered or critically endangered, or equivalents) on any locally, nationally or internationally accredited and recognised list of species under conservation.

Tolerance: the capacity for a plant species or community to withstand a cycle of disturbance and recovery.

Trail-based fragmentation: patterns and processes related to fragmentation but caused by linear clearing for trail infrastructure that results in the loss of vegetation and animal habitat and modification of the adjacent areas causing edge effects of varying degree.

Weed: non-native plant species that can invade natural ecosystems and often have economic and environmental impacts (Richardson et al., 2000; McDougall et al., 2011).

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Chapter 1. Introduction

1.1 Nature-based tourism and recreation

Tourism and recreation form one of the world's largest and most rapidly-growing industries with over 1.1 billion people travelling internationally in 2014 and even greater numbers recreating in their local area (Christ et al., 2003; Cornelissen, 2005; Geneletti and Dawa, 2009; Newsome et al., 2013; UNWTO, 2015). The contribution of tourism alone to global GDP has increased over 6-fold within the last 13 years from US\$1.05 trillion in 2001 to US\$7.6 trillion in 2014 (WTTC, 2015a). One in ten of the world's working population are employed by the tourism and recreation industry (WTTC, 2015a). With a rise in discretionary income, vehicle ownership and leisure time, tourism and recreation are now a part of the lives of at least 1 billion people (WTTC, 2015b). This rapid uptake has helped stimulate local and national economies (WTTC, 2015a) as well as providing benefits for education, human health and wellbeing, especially where activities take place in natural settings (World Health Organisation, 2005; Maller et al., 2009).

Nature-based tourism and recreation is an increasingly important sector of the tourism and recreation industry (Buckley, 2004; Kuenzi and McNeely, 2008; Buckley, 2010). Essentially nature-based tourism encompasses the activities that visitors take part in during a holiday whereby they engage with nature in a location away from their home environment (Newsome et al., 2013; Bell et al., 2007), while nature-based recreation is defined as the nature-based activities that people engage in within a natural or semi-natural location as part of their leisure time (Nicholls, 2006; Bell et al., 2007). Nature-based tourism and recreation provide a range of visitor activities from thrill-seeking and adventure activities, practising skills and keeping mentally and physically fit to learning about cultural and natural history, achieving solitude and socialising (Newsome et al., 2013; Spenceley et al., 2015). Over the past 50 years, this sector has grown and diversified rapidly (Roovers et al., 2004; Balmford et al., 2009; Monz et al., 2010a; Newsome et al., 2013) with nature-based activities a primary focus of at least 20% of all tourism ventures globally (Buckley, 2010).

Countries in North America, Europe, Asia and Oceania are experiencing some of the most rapid growth in nature-based tourism and recreation (Cole and Landres, 1996; Bell et al., 2007; Cordell et al., 2008; Buckley, 2010; Geneletti and Dawa, 2009; Balmford et al., 2009; Tourism Australia, 2012). In Australia, for example, there are between 85 and 105 million visits to natural areas each year, including many domestic visitors with 73% of Australian adults recreating in natural areas (Australian Bureau of Statistics, 2013; Newsome et al., 2013;

Convention on Biological Diversity, 2014; Spenceley et al., 2015). Many of the most popular nature-based tourism and recreational activities in these areas are trail-based, including hiking, mountain-biking and running (Nvight, 1996; Queensland Government, 2007; Cordell et al., 2008; Balmford et al., 2009; Olive and Marion, 2009). As a result of their popularity, there is increasing development of trails with over 126,000km of formalised recreational trails in the USA alone used by over 137 million people each year (Outdoor Foundation, 2010; US National Parks Service, 2014). Trail-based activities and trails are also increasing in popularity in regions comparatively new to the tourism and recreation market, such as East Asia (Leung and Marion, 2000; Newsome et al., 2013; Zhong et al., 2015).

While trail-based tourism and recreation provides increasing access to natural areas allowing people to experience and enjoy them, they also have environmental impacts. The global coverage of natural areas is already in decline, as anthropogenic activities such as urbanisation, agricultural expansion and resource extraction cause increasing habitat loss and disturbance (Myers et al., 2000; Van der Duim and Caalders, 2002; Christ et al., 2003; Newsome et al., 2013). While in some natural areas anthropogenic activities are not permitted, or are restricted, trail-based tourism and recreation are often permitted and indeed, promoted (Spenceley et al., 2015). For managers of natural areas, the impacts of this type of use are important to understand to limit the degradation of these areas and to ensure that tourism and recreation do not detract from their ecological value. As a result, there is increasing research interest in enhancing the sustainability of nature-based tourism and recreation in natural areas, including understanding and mitigating impacts caused by recreational trails (Liddle, 1975; Cole, 1989; Farrell and Marion, 2001; Cole, 2004; McDougall and Wright, 2004; Pickering and Hill, 2007; Kuenzi and McNeely, 2008). This is part of the broader discipline of recreation ecology (Cole, 1989; Liddle, 1997; Marion and Linville, 2000; Cole, 2004).

1.2 Recreation ecology

Recreation ecology is the scientific study of the impacts of nature-based tourism and recreation on natural and semi-natural environments (Liddle, 1997). Impacts are diverse and their type and severity varies widely depending on the activity and location (Liddle, 1997). Broadly speaking, the effects of nature-based tourism and recreation on the environment can be grouped into three categories: those due to (1) transport, (2) activities and (3) infrastructure (Van der Duim and Caalders, 2002). Combined, these impact categories form the foundations of the nature-based tourism and recreation industry's global ecological footprint (Gössling et al., 2002).

To date, the majority of recreation ecology research looking at the terrestrial environmental impacts of nature-based tourism and recreation has focused on the impacts of activities on vegetation and soils. Specifically, this includes comparing among different nature-based activities such as hiking, mountain-biking and horse-riding (Rickard et al., 1994; Wilson and Seney, 1994; Deluca et al., 1998; Törn et al., 2009; Pickering et al., 2011), different intensities of use (Young and Gilmore, 1976; Cole and Bayfield, 1993; Kutiel et al., 1999; Lemauviel and Rozé, 2003; Talbot et al., 2003; Hill and Pickering, 2009; Pickering and Growcock, 2009; Burns et al., 2013), different ecosystems including rating their tolerance to disturbance (Rickard et al., 1994; Pickering and Hill, 2007; Bernhardt-Römermann et al., 2011) and different temporal scales including assessing recovery from disturbance (Bayfield, 1979; Whinam et al., 2003; Scherrer and Pickering, 2006; Growcock and Pickering, 2011). While some activities do not require trails (e.g. paragliding, rock-climbing, geocaching etc.), a large proportion of the recreation ecology literature has focused on trail-based activities such as hiking and mountain-biking (Marion and Leung, 2001; Cole, 2004; Pickering et al., 2011). Recent reviews have synthesised many of these results demonstrating how the type, intensity, location, timing and behaviour affect the type, scale and severity of impacts (Liddle, 1997; Cole, 2004; Monz et al., 2010a; Monz et al., 2010b; Pickering, 2010; Pescott and Stewart, 2014).

While research on the impacts of nature-based tourism and recreational activities is well developed, there is comparatively less work focusing on how the infrastructure provided for these activities causes environmental impacts. While large infrastructures such as eco-resorts can have some of the most severe direct impacts through the removal of vegetation and soil (Kelly et al., 2003; López-Pujol et al., 2003; Priskin, 2003; Leyva et al., 2006; Ballantyne and Pickering, 2013), infrastructures such as trails can be developed rapidly and over large spatial scales, often including illegal or informal development by users themselves (Leung and Marion, 2000; Marion and Leung, 2004; Ballantyne et al., 2014). While trails are created partly as a function of use, they have additional impacts separate to use-related impacts (Marion et al., 2011). These include impacts relating to their construction and maintenance, and also simply their presence as corridors of disturbance (Figure 1.1). These impacts have been comparatively poorly studied in terms of their effect on vegetation and soils, with a recent review only finding 59 original research papers on this topic globally (Chapter 2).

1.3 Recreational trail impacts

Trails are among the most common forms of infrastructure used for nature-based tourism and recreation (Leung and Marion, 2000; Marion and Linville, 2000; Cole, 2004; Marion and Leung, 2004). They are highly diverse; from bare earth trails to concrete and tarmac paths, single

overland tracks to complex geometrical networks, single-use trails to multi-use trails, formally-designated to informally user-created and from transient use routes to permanent landscape features. As a result, the impacts recreational trails have on vegetation and soils varies considerably depending on numerous factors relating to the nature of the trail infrastructure, its use and the ecosystem (Figure 1.1).

The initial impacts of recreational trail infrastructure arise from their construction. This can include the removal of vegetation, which for hardened trails often requires heavy machinery, grading of the surface, delivery and laying of the materials used for surfacing and ultimately, the development of a barren, exposed linear corridor (Cole, 2004; Leung et al., 2011). The work zone for this process can often disturb vegetation more than 10m from the trail itself, especially when heavy machinery is used (Buckley, 2004; Ledoux, 2004). Hardened trails (e.g. tarmac tracks/roads) can inhibit infiltration increasing the rate of flooding and surface flow (Quintana-Ascencio et al., 2007). The use of 'foreign' substrates (e.g. dolomite gravel in an acidic environment) can alter trail edge soil conditions and vegetation composition (Godefroid and Koedam, 2004; Müllerová et al., 2011). However, trails with no substrate (bare tracks) are vulnerable to erosion, widening, compaction, root exposure and other damage to vegetation and often degrade over time (Farrell and Marion, 2001; Hill and Pickering, 2006; Marion and Leung, 2011).

Trail maintenance can also cause impacts through realigning, draining, re-surfacing, cutting, mowing, spraying and grading (Goosem, 2007; Starr-Keddle, 2011; Goosem, 2012). Maintenance on the trail reduces the likelihood of many species re-establishing and so vegetation cover is subsequently low except for the most disturbance-tolerant species. Cutting vegetation along the edge of trails to maintain the openness of trail routes directly affects plant growth and reproduction promoting more ruderal species and graminoids with high productivity (Kleier et al., 2009). Maintenance by cutting verges, herbicide spraying and stabilising verge slopes can selectively remove certain species that are less tolerant of these stressors changing local vegetation composition (Clark et al., 1998; Starr-Keddle, 2011), structure and microclimate (Delgado et al., 2007; Goosem, 2007).

Finally, the actual presence of the trail can cause significant impacts, especially where abiotic conditions of the undisturbed environment contrast strongly with those along the trailed environment, e.g. trails through closed rainforests. The presence of a trail corridor reduces canopy cover resulting in increased radiation and drying of the understory, along with increases in soil temperature through a reduced albedo from the trail surface and changes in air temperature and wind profiling (Delgado et al., 2007; Pohlman et al., 2007). These more

exposed conditions can result in higher cover of novel disturbance-tolerant species, wind-dispersing species and weeds in forests (Bright, 1986; Hamberg et al., 2008; Atik et al., 2009). While most of these effects are largely concentrated to the direct local (on-trail) and indirect local scale (edge effects), the magnitude of the edge effects can sometimes extend 20m from the trail itself (Hamberg et al., 2008; Malmivaara-Lämsä et al., 2008) and where trails exist as networks these impacts become cumulative across the landscape (Ballantyne et al., 2014; Figure 1.1).

When the impacts of the recreational trails themselves are then combined with intense recreational use, trail impacts can be even greater including trampling, plant collecting, erosion, pollution, weed-spread, noise and so on. However, recreational use is often rather transient, whilst the effects of the trails themselves are more permanent. In this respect, it is important to increase our knowledge about how trail infrastructures affect vegetation, especially threatened plant communities. While recreational trails are increasing across the globe exposing more and more natural areas to disturbance, it is important to prioritise research in those communities already at risk of extinction.

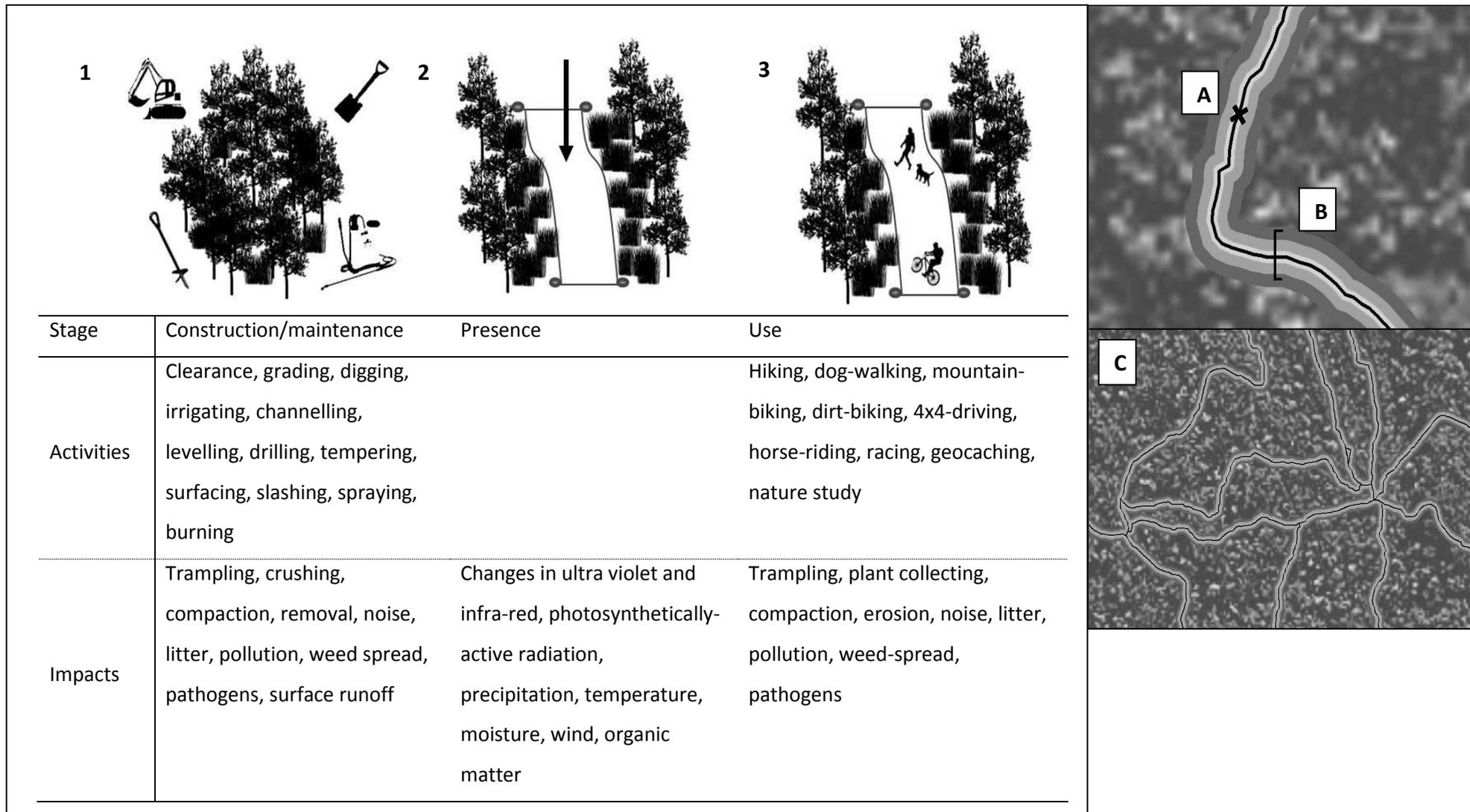


Figure 1.1 Three primary ways in which trails can affect vegetation and soils (1. construction and maintenance, 2. presence and 3. use) and the scales at which they act (A. direct local, B. indirect local and C. dispersed landscape).

1.4 Recreational trails and threatened plant communities

Alongside the rise in nature-based tourism and recreation, there has been a decline in the coverage of natural ecosystems in which people can engage in nature-based activities (Lindenmayer and Burgman, 2005; Balmford et al., 2009). This is largely a result of anthropogenic activities such as urbanisation, agricultural expansion and resource extraction causing habitat loss, spread of invasive species and climate change (Lindenmayer and Burgman, 2005; Butchart et al., 2010). There are few datasets worldwide accurately assessing the total number of threatened ecosystems, although the International Union for the Conservation of Nature (IUCN) is in the process of compiling a representative system due to be launched in late 2015 (<http://www.iucnredlistofecosystems.org/>). Recent studies have shown however, that many of the world's ecosystems are in decline, including thousands of plant communities (Ellis and Ramankutty, 2008; Walker and Salt, 2012). Many of these are under increasing use for nature-based tourism and recreation, including trail development (Rickard, 1994; Rouget et al., 2003; Turpie and Joubert, 2004; Ballantyne et al., 2014).

With more people accessing increasingly threatened natural areas for nature-based tourism and recreation, threatened plant communities are at an increasing risk from recreational trails. Some of the most vulnerable communities occur in locations that are also particularly attractive for nature-based tourism and recreation. This includes threatened communities externally fragmented and isolated by urban growth which are now close to dense urban populations who wish to use these 'green spaces' for recreational purposes such as hiking, mountain-biking and running (Matlack, 1993; Stenhouse, 2004; Ballantyne et al., 2014). It also includes plant communities which occupy specific ecological niches that make them rare and where conditions are also attractive to visitors, e.g. mountain tops, cliff-edges and waterfalls for hiking, rock-climbing and swimming (Ballantyne and Pickering, 2012). Communities which are inherently attractive to visitors in their own right, such as botanical tourist trails through flower-rich sandplain herbfield communities in Western Australia, are also threatened by visitation and subsequent trail development (Phillips and Newsome, 2001; Priskin, 2003; Ballantyne and Pickering, 2012).

While activities such as road development, resource extraction and commercial harvesting are not permitted, or are restricted, in many threatened plant communities, trail-based tourism and recreation are often permitted and indeed, promoted as a rationale for the area's conservation. While trail-based tourism and recreation provide opportunities for environmental education and the maintenance of human health and wellbeing, their impacts must be closely monitored. Managers of threatened plant communities have a dual mandate to both promote conservation including through

visitation, but also to actively apply conservation measures by reducing anthropogenic disturbances. While tourist and recreational visitors are an important component, it is important that any impacts of visitation are fully understood and mitigated, which requires considerable research effort. Research is especially critical for permanent infrastructures such as trails which are less well studied and likely to cause different types, scales and severities of impacts to some of our most threatened plant communities (Newsome et al., 2013; Ballantyne et al., 2014). By minimising such impacts we can maintain the resilience of threatened plant communities to other larger-scale changes such as climate change and ultimately more adequately conserve the species and ecosystem services they contain (Chiesura, 2004; Maller et al., 2006).

1.5 Threatened plant communities and trails in Australia

Australia has a high diversity of native flowering plants with over 17,700 species, 93% of which are endemic (Australian Government, 2011). These plants form numerous and diverse communities and the terrestrial ecosystems these communities support provide an estimated AU\$1,300 billion per year in ecosystem services (Brooks et al., 2006; Zachos and Habel, 2011). Unfortunately, Australia also has one of the highest rates of natural vegetation clearance globally (Pitman et al., 2002; Lindenmayer and Burgman, 2005) with over 1,100 species and at least 65 plant communities at risk of extinction nationally (Australian Government, 2004; 2011; 2015). The total number of threatened plant communities varies among states however, with Queensland, the second largest state in the country, having 1,385 different plant communities of which 789 are listed as threatened; the highest among states (Queensland Government, 2015). It is therefore vital to know more about how new and emerging types of human disturbances may impact these communities, including impacts from recreational trails.

In this thesis, the impacts of recreational trails were assessed in three different threatened plant communities in Australia. Communities were selected to: (1) differ in dominant growth forms, (2) vary in composition and structure, (3) represent different climatic zones, (4) all be listed (or currently be in the process of being listed) as threatened at either national or state level and (5) contain a variety of recreational trails. Specifically, the impacts of recreational trails were assessed in Windswept Feldmark which is an alpine plant community threatened by climate change and fire, Grey Box grassy woodland which is a Mediterranean-climate woodland threatened by agriculture and urbanisation and Tall Open Blackbutt forest which is a subtropical hardwood forest threatened by urbanisation (Table 1.1).

Image	Community	Description	Dominant Species	Structure (height and % veg. cover)	Species richness per site	Climate (Köppen-Geiger)
	Windswept Feldmark	Short alpine heathland on high wind-exposed alpine ridges of Kosciuszko National Park. It occurs on shallow soils and has low plant diversity and cover but high endemism.	<i>Epacris gunnii</i> (alpine shrub)	Canopy 9cm, 54% Understorey 4cm, 15%	23	Alpine Tundra
	Grey Box Grassy Woodland	Sparse-mid dense grassy woodland from central New South Wales to the South Australian coast on low slopes and plains. It occurs on soils derived from alluvial deposits and has high herb/graminoid diversity.	<i>Eucalyptus microcarpa</i> (temperate hardwood)	Canopy 19m, 25% Midstorey 3m, 20% Understorey 95%	200	Mediterranean
	Tall Open Blackbutt Forest	Subtropical open forest on coastal slopes from south-east Queensland to central New South Wales. It occurs on sedimentary-metamorphic rocks, has a complex structure and high diversity.	<i>Eucalyptus pilularis</i> (subtropical hardwood)	Canopy 27m, 38% Midstorey 3m, 7% Understorey 41%	120	Warm Subtropical

Table 1.1 Outline of the three threatened plant communities studied in this thesis detailing community descriptions, dominant species and climate as well as both structural and compositional attributes.

Australia has a rich and diverse alpine region in southern New South Wales and north-eastern Victoria and in Tasmania, with a total of at least 10 plant communities currently listed as threatened (Forest Practises Authority, 2013; New South Wales Government, 2015; Victorian Government, 2015). These communities are largely threatened by climate change, changing land use and grazing (Scherrer and Pickering, 2001; Hughes, 2003). The communities are important strongholds for many of the 91 plant species endemic to the Australian alpine regions including several listed as threatened by the Australian Government such as *Ranunculus anemoneus*, *Colobanthus curtisiae* and *Rytidosperma pumilum* (McDougall and Walsh, 2007; New South Wales Government, 2011). Some of the communities occur in popular destinations for visitors who seek to conquer high mountain peaks, take part in extreme sports and use long-distance hiking trails (Pickering and Buckley, 2003). The alpine zones in the Snowy Mountains of New South Wales alone receive up to 100,000 summer visitors a year, with many people using the extensive network of > 127km of trails (Johnston and Pickering, 2001; Pickering and Buckley, 2003; Growcock, 2006; Hill and Pickering, 2006). Many of these trails traverse threatened alpine plant communities that have limited altitudinal ranges such as Windswept Feldmark (McDougall and Wright, 2004; McDougall and Walsh, 2007).

Australia is also among the most urbanised countries in the world with over 85% of the total population residing in cities and towns (Byrne et al., 2010; Australian Bureau of Statistics, 2014). This process of urbanisation has taken place largely around Australia's south and east coast and has caused the loss and fragmentation of many terrestrial ecosystems especially in south-east Queensland, the Sydney region, Melbourne and Adelaide (Lindenmayer and Burgman, 2005). As a result, many threatened plant communities in coastal peri-urban areas such as forest and woodland remnants have become both important areas for conservation, but are also often intensively-used for trail-based recreation (Chiu and Kriwoken, 2003; Stenhouse, 2004; Ballantyne et al., 2014). In south-east Queensland alone, there are at least 2,000km of formalised recreational trails, with many traversing threatened plant communities such as Swamp Tea-tree and Tall Open Blackbutt forest (Daly and Daly, 2009; Ballantyne et al., 2014). In South Australia too there are extensive trails with particularly dense networks around the Adelaide region including through many threatened plant communities such as Grey Box and Peppermint Box grassy woodlands (Ballantyne and Treby, 2015).

1.6 Aims

This thesis aims to highlight the current state of research into recreational trail impacts globally and then addresses important knowledge gaps using research conducted in the three Australian threatened plant communities. The results of the thesis provide useful insights into how recreational trails impact vegetation, with a specific focus on impacts on threatened plant communities.

The first part of the research presented in this thesis is based on a global systematic quantitative literature review analysing what is known and unknown about the impacts of recreational trails on vegetation and soils. This forms **Chapter 2** and answers **Aim 1: What is the current state of research on trail impacts on vegetation and soils?** The results of this literature review found limited research assessing the impacts of trail infrastructure in threatened plant communities. Therefore, the rest of the thesis focuses on how and why recreational trails may be a concern for the conservation of threatened plant communities. This is assessed in **Chapters 3 - 7** and answers **Aim 2: Do recreational trails have impacts on threatened plant communities?** From the literature review it was also clear that recreational trails can have impacts at different spatial scales and so the thesis also analyses trail impacts across different spatial scales within threatened plant communities in **Chapters 3 - 7** addressing **Aim 3: Do trail impacts occur at direct local, indirect local and cumulative landscape scales?** The literature review also showed that while biodiversity is measured as three facets according to Noss (1990), most existing research assessing impacts of recreational trails focused on compositional, and to some degree, structural impacts, with limited research assessing functional impacts. Therefore I analysed trail impacts across all three facets of biodiversity in the threatened plant communities in **Chapters 3 - 6** addressing **Aim 4: Do trail impacts affect the structure, composition and function of threatened plant communities?** Finally, the literature review showed that little research compared impacts among different types of trails including assessing their relative impacts on threatened plant communities. Therefore in this thesis I also compared impacts of different types of trails at different spatial scales on compositional and structural biodiversity in **Chapters 5 and 6** addressing **Aim 5: Do impacts differ in type and severity among different types of recreational trail?** (Figure 1.2). The final chapter, **Chapter 8**, is a general discussion summarising the key results from across the preceding chapters in relation to the thesis aims and the literature. It provides recommendations for future research and the management of recreational trails including in threatened plant communities.

1.7 Thesis structure

The structure of this thesis consists of a general introduction (Chapter 1) followed by six published and submitted papers (Chapters 2 – 7) and a general discussion (Chapter 8) (Figure 1.2). This thesis structure is in accordance with Griffith University guidelines and policy regarding a thesis in the form of published and unpublished papers (Appendix 1).

As a result of this layout, there is some repetition including in the introduction in study site and plant community descriptions, methods used and in the references among chapters. During my PhD candidature I also legally changed my surname to that presented at the front of the thesis, but retained my original surname (Ballantyne) on all published papers submitted as part of this thesis.

Published and submitted papers included as results chapters

Chapter 2: Ballantyne, M. and Pickering, C.M., (2015) The impacts of trail infrastructure on vegetation and soils: current literature and future directions. *Journal of Environmental Management*. **164**, 53-64.

Chapter 3: Ballantyne, M., Pickering, C.M., McDougall, K.L. and Wright, G.T., (2014) Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps. *Australian Journal of Botany* **62**, 263-275.

Chapter 4: Ballantyne, M. and Pickering, C.M., (2015) Recreational trails as a source of negative impacts on the persistence of keystone species and facilitation. *Journal of Environmental Management* **159**, 48-57.

Chapter 5: Ballantyne, M., Treby, D.L., Quarmby, J. and Pickering, C.M., (in review) Comparing the impacts of different types of recreational trails on vegetation: lessons for conservation and management.

Chapter 6: Ballantyne, M. and Pickering, C.M., (2015) Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure. *Journal of Environmental Management* **159**, 94-105.

Chapter 7: Ballantyne, M., Gudes, O. and Pickering, C.M., (2015) Recreational trails are an important cause of fragmentation in endangered urban forests: a case-study from Australia. *Landscape and Urban Planning* **130**, 112-124.

Other publications completed during candidature but not included in this thesis:

Conference abstracts

Ballantyne, M., Pickering, C.M. and Gudes, O., (2014) How formal and informal mountain biking trails result in the reduction, degradation and fragmentation of endangered urban forest remnants (conference and extended abstract). Seventh International Conference on Monitoring and Management of Visitors in Recreational and Protected Areas, Tallinn, Estonia, 20 - 23 August. pp. 155-157.

Ballantyne, M., (2014) The use of apps to communicate species conservation and learning (conference and abstract). Association of Friends of Botanic Gardens National Conference, Gold Coast, Australia, 9 August.

Ballantyne, M. and Pickering, C.M., (2012) Impacts of trail networks on rare and threatened plant communities in Australia (conference and extended abstract). Sixth International Conference on Monitoring and Management of Visitors in Recreational and Protected Areas, Stockholm, Sweden, 21 - 24 August. pp. 364-365.

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Ballantyne, M., (2012) Fragmentation impacts of trail networks on threatened plant communities in south-east Queensland (conference and abstract). Environmental Futures Research Institute Student Research Symposium, Nathan, Australia, 21 September.

Related published papers

Ballantyne, M. and Pickering, C.M., (2015) Shrub facilitation is an important driver of alpine plant community diversity and functional composition. *Biodiversity and Conservation* **24**, 1859-1875.

Rankin, B.L., Ballantyne, M. and Pickering, C.M., (2015) Tourism and recreation listed as a threat for a wide diversity of vascular plants: a continental scale review. *Journal of Environmental Management* **154**, 293-298.

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Book chapters

Pickering, C.M. and Ballantyne, M., (2012) Orchids: an example of charismatic megaflora tourism? In: A. Holden and D. Fennell (eds.) *Handbook of Tourism and the Environment*. Routledge Publishing, London, UK. pp. 192-199.

Industry monographs

Ballantyne, M. and Treby, D.L., (2015) The impacts of recreational trails in Grey Box grassy woodland in the Adelaide region. Scientific report for the Department of Environment, Water and Natural Resources, South Australia, Australia.

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Other online publications

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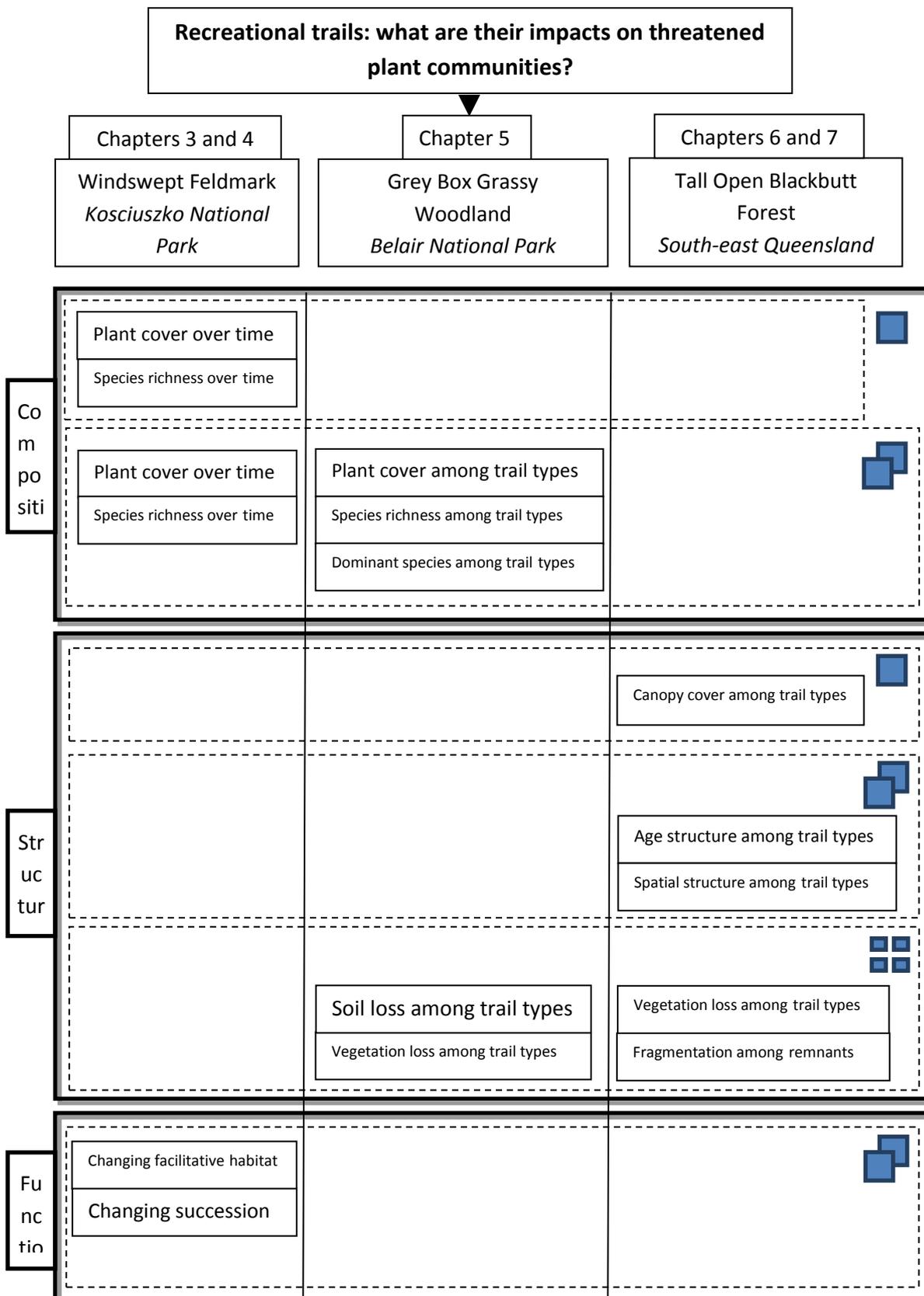


Figure 1.2 Summary of the structure of the thesis assessing trail impacts in three threatened plant communities. The cells describe the main variables to be tested in each community separated into

compositional, structural and functional impacts (left-hand side) and among direct local (single square), indirect local (double square) and cumulative landscape scales (multi square).

1.8 The threatened plant communities

To highlight the impacts of recreational trails on threatened plant communities, three different plant communities were chosen (Figure 1.3, Table 1.1). Details of these three communities are presented here.

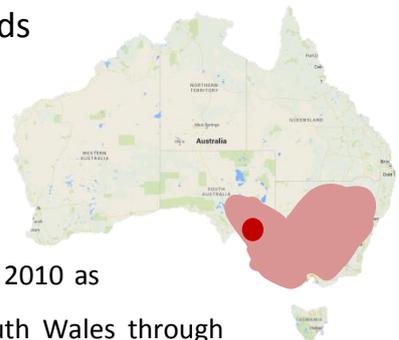
Windswept Feldmark

Windswept Feldmark is an alpine shrub-dominated plant community currently under final determination by the New South Wales Threatened Species Conservation Regulation 2010 as critically endangered (New South Wales Scientific Committee, 2015). The community is restricted to < 28.5 ha of wind-exposed ridgelines along the Main Range of Kosciuszko National Park, New South Wales (Costin et al., 2000). The community is dominated by the small (< 10cm high) prostrate sclerophyllous shrub *Epacris gunnii* which grows from windward to leeward sides of the ridgelines in a regular pattern of succession. The patchwork of shrubs form a network of protective microhabitats that facilitate the establishment of around 50% of all other species in the community, while the exposed areas in between shrubs support more stress-tolerant species such as cushion plants and grasses (Figure 1.3a). An unsurfaced, roughly 1.5m wide recreational trail primarily used for hiking, roughly dissects parts of this rare plant community in half and likely acts as a source of localised disturbance and as a barrier to small-scale ecological processes such as facilitation (McDougall and Wright, 2004).



Grey Box grassy woodland and derived native grasslands

Grey Box grassy woodland is a Mediterranean grass and *Eucalyptus*-dominated plant community listed under the Australian Environment Protection and Biodiversity Conservation Act 1999 and the New South Wales Threatened Species Conservation Regulation 2010 as endangered. It occurs across a wide region from central New South Wales through northern Victoria into coastal South Australia. It has been extensively cleared and fragmented by agricultural practises and urbanisation in the past and is now reduced to around 10-15% of its original range as scattered remnants. The community is dominated by a canopy of *Eucalyptus microcarpa* and *E. camaldulensis* and has a highly diverse understorey of mixed native and exotic



graminoids and herbs with species richness often > 200 per site (Figure 1.3b). Many of the remnants are close to cities and agricultural areas where locals use them for recreation. Trail development has been extensive in these woodlands including both trails built by managers and trails informally-created by users resulting in diverse networks of different types of trails that likely have varying effects on vegetation.

Tall Open Blackbutt forest

Tall Open Blackbutt forest is a sub-tropical hardwood *Eucalyptus*-dominated plant community listed under the Queensland Vegetation Management Act 1999 as endangered. It is predominantly coastal occurring from south-east Queensland



through to central New South Wales on sedimentary and metamorphic plains. The forest community has been extensively cleared and fragmented for urban development and is now reduced to around 15-20% of its former area. The community has a complex structure dominated by *Eucalyptus pilularis*, *E. microcorys*, *E. tindaliae* and *Corymbia intermedia* and with a well-developed midstorey of sclerophyllous shrubs, she-oaks, ferns and graminoids (Figure 1.3c). The community's close proximity to dense urban populations means it is popular for recreation, much of which is informal. The numerous small remnants of this forest are often unprotected and their open structure provides easy access to create often complex networks of multi-use informal trails (Ballantyne et al., 2014).



1.3a Windswept Feldmark plant community endemic to Kosciuszko National Park, Australian Alps bioregion, New South Wales. Note the simple community structure and regular 'waveform' of *Epacris gunnii* shrubs which dominate the community and are an important keystone species.



1.3b Grey Box grassy woodland plant community in Belair National Park, Flinders-Lofty Block bioregion, South Australia. Note the more complex structure of the community with a distinct grass-dominated ground layer and a relatively sparse *Eucalyptus* and *Acacia*-dominated mid and canopy layer.



1.3c Tall Open Blackbutt forest plant community found between Brisbane and Gold Coast, south-east Queensland bioregion, Queensland. Note the complex structure of this community with a dense grass and fern – dominated understorey, shrubby midstorey and mid-dense canopy of tall hardwood *Eucalyptus* and *Corymbia* species.

Figure 1.3 Examples of the three threatened plant communities studied in this thesis. Photographs by M. Runkowski.

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Chapter 2. The impacts of trail infrastructure on vegetation and soils: current literature and future directions

The previous chapter presents the background, aims, study sites and structure of the thesis. The first results chapter of the thesis is a systematic quantitative literature review that assesses the current state of literature on the impacts of recreational trail infrastructure on vegetation and soils. It identifies the knowledge gaps that are then addressed in Chapter 3 - 7.

This chapter consists of the published version of a paper co-authored with my principle supervisor. The bibliographic details of the paper, including all authors, are:

Ballantyne, M. and Pickering, C.M., (2015) The impacts of trail infrastructure on vegetation and soils: current literature and future directions. *Journal of Environmental Management* **164**, 53-64.

My contribution to the paper involved: the compilation of the systematic quantitative literature review database, data analyses, drafting of the manuscript, tables and figures and submission to the journal.

A full copy of this paper is available at the publisher's website via the following link:

<http://www.sciencedirect.com/science/article/pii/S030147971530236X>

Chapter 3. Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps

The previous chapter looked at the current state of literature on the impacts of trail infrastructure on vegetation and soils. The literature review (Chapter 2) showed that there is limited research addressing the impacts of trail infrastructure on threatened communities, and moreover, that research on temporal changes caused by trails is also sparse. This chapter therefore presents results on the impacts of a hiking trail on the composition of the critically endangered Windswept Feldmark alpine plant community. It assesses the effects of the trail 10 years after initial vegetation surveys.

This chapter consists of the published version of a paper co-authored with my principle supervisor and the authors of the original survey in 2003. In 2013 I repeated that survey with one of the original authors (Wright) and my principle supervisor. The bibliographic details of the paper, including all authors, are:

Ballantyne, M., Pickering, C.M., McDougall, K.L. and Wright, G.T., (2014) Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps. *Australian Journal of Botany* **62**, 263-275.

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Sustained impacts of a hiking trail on changing Windswept Feldmark vegetation in the Australian Alps

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Abstract. Damage to vegetation from tourism and recreation includes the impacts of hiking trails, which may favour trampling-tolerant plants over those that are more sensitive to this type of disturbance. To assess how continued use of a hiking trail coupled with changes in local climate affect a rare Australian alpine plant community, we compared plant composition at different distances from a trail in 2013 during wetter conditions with that 10 years prior during a drought in 2003. In both years, only a few trampling-tolerant graminoids and cushion plants were found on the trail surface, which runs along the ridgeline. Species richness and cover in both surveys generally increased with distance from the trail, but there were differences between the windward and leeward sides of the trail. This included increased abundance of some species but continued disruption of shrub succession on the leeward side of the trail. There was an overall increase in species richness between the two surveys, and changes in the abundance of many species independent of trampling effects, possibly reflecting the more favourable/wetter conditions for plant growth in 2013. These results suggest that changes in climatic conditions can affect community composition, but that this has not negated the impact of the hiking trail on this rare community. With average temperatures increasing, and snow cover declining in the Australian Alps, it is likely that there will be even more changes in the Windswept Feldmark, including the potential colonisation of these ridges by more competitive species, such as graminoids, at the expense of the dominant shrub and some herbs that are already adversely affected by trampling. Longer term monitoring of this rare community is imperative to better understand community processes in relation to the impacts of trail use and climate change. Management options to reduce these impacts are discussed.

Additional keywords: climate change, shrubs, threatened communities, tourism impacts.

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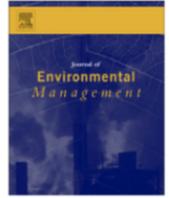
Chapter 4. Recreational trails as a source of negative impacts on the persistence of keystone species and facilitation

The previous chapter assessed the impacts of a hiking trail on the composition of vegetation in the critically endangered Windswept Feldmark plant community over a 10-year period. It found that there were large-scale climatic influences on community composition, but also sustained localised disturbances from the hiking trail. In combination, these factors increased the proliferation of graminoids, reduced the cover of the dominant shrub, caused a barrier affecting the succession of the dominant shrub and caused a decline in less tolerant herbs. Additionally, the literature review (Chapter 2) showed that there has been very limited research on the functional impacts of recreational trails. This next chapter determines how the hiking trail reduces the cover of the dominant shrub in the Windswept Feldmark, and whether this affects the abundance of species dependent on the shrub for facilitation; an important functional process in this community.

This chapter consists of the published version of a paper co-authored with my principle supervisor. The bibliographic details of the paper, including all authors, are:

Ballantyne, M. and Pickering, C.M., (2015) Recreational trails as a source of negative impacts on the persistence of keystone species and facilitation. *Journal of Environmental Management* **159**, 48-57.

My contribution to the paper involved: field-work, data collection, all data analyses, drafting of the manuscript, tables and figures and submission to the journal.



Research paper

Recreational trails as a source of negative impacts on the persistence of keystone species and facilitation



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ABSTRACT

Hiking trails, which are among the most common forms of infrastructure created for nature-based tourism, can alter key ecological processes. Trails can damage plants that facilitate the establishment and growth of other species leading to changes in community and functional composition. This can be a particular concern in harsh alpine ecosystems where plant communities are often dominated by one or two keystone species that provide shelter to a suite of beneficiary species. We analysed how a hiking trail affects interspecific facilitation by a dominant trampling-sensitive nurse shrub in the highest National Park in Australia. First we assessed the effects of the trail on the abundance, size and density of the nurse shrub at different distances from the trail. We then compared species richness and composition between areas in, and out, of the nurse shrub's canopy at different distances from the trail. To better understand why some species may benefit from facilitation and any effects of the trail on the quality of facilitation we compared functional composition between quadrats using community trait weighted means calculated by combining plant composition with species functional traits (canopy height, leaf area, % dry weight of leaves and specific leaf area). The abundance, size and density of nurse shrubs was lower on the trail edges than further away, particularly on the leeward edge, where there was more bare ground and less shrub cover. There were differences in species richness, cover, composition and functional composition in and outside the nurse shrub canopy. The shrubs appeared to facilitate species with more competitive, but less stress tolerant traits (e.g. taller plants with leaves that were larger, had high specific leaf area and low dry matter content). However, despite reductions in nurse shrubs near the trail, where they do exist, they appear to provide the same 'quality' of facilitation as nurse shrubs further away. However, longer-term effects may be occurring as the loss of nurse shrubs alters the wind profile of the ridgeline and therefore succession. The use of a steel mesh walkway along the trail may facilitate the regeneration of nurse shrubs and other plants that require protection from wind. Our results highlight the importance of diversifying recreation ecology research to assess how trails affect important ecological processes.

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Chapter 5. Comparing the impacts of different types of recreational trails on vegetation: lessons for conservation and management

The previous chapter looked at the functional impacts caused by a hiking trail on the critically endangered Windswept Feldmark plant community. It found that the trail acts as a barrier changing the usual wind profile of the ridgeline and therefore inhibiting the continued windward-leeward succession of the dominant shrub with fewer, large shrubs and increased bare ground on the leeward side of the trail. This has directly reduced the amount of facilitative habitat provided by the shrub to 45% of other plant species in the community that rely on it. However, where the shrub still exists it provides the same quality of facilitation for these species.

The literature review (Chapter 2) showed that there has been surprisingly little research comparing the effects of different types of recreational trails on the composition of vegetation along trail edges. The next chapter examines this issue by comparing the composition and condition of edge vegetation along five different types of trails within an endangered Grey Box grassy woodland remnant.

This chapter consists of the in review manuscript of a paper co-authored with my principle supervisor and two colleagues; Treby who assisted with field-work and drafting of the manuscript and Quarmby who helped organise funding and equipment for field-work and helped disseminate the research results in an industry report. The bibliographic details of the paper, including all authors, are:

Ballantyne, M., Treby, D.L., Quarmby, J. and Pickering, C.M., (in review) Comparing the impacts of different types of recreational trails on vegetation: lessons for conservation and management.

My contribution to the paper involved: field-work logistics, field-work, data collection, data analyses, drafting the manuscript, production of tables, maps and figures and submission to the journal.

Comparing the impacts of different types of recreational trails on vegetation: lessons for conservation and management

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Abstract

Nature-based tourism and recreation are popular but have a range of impacts on natural areas. This includes impacts of recreational trails, but which types of trails have the greatest impact on vegetation? We compared the types and severity of impacts on vegetation among five different trails including small, medium and large bare earth trails, medium gravel trails and large tarmac trails in an endangered urban woodland ecosystem. First, the extent, width, area and types of trails were mapped within a large remnant of the woodland that is close to a major city. Then, using stratified random sampling, soil and vegetation variables were measured in quadrats at three distances from the edge of the five types of trail, with 10 replicate sites per trail type and single quadrats at 10 control sites (i.e. total 60 sites, 160 quadrats). All the trails resulted in vegetation loss both on the trail surface but also along the edge of the trails as well as changes in vegetation composition, including reductions in shrubs and bulbs. Medium (2.5 m width) bare earth trails, which were the most common (50% of trails), resulted in the greatest soil loss (6.8 million m³) and vegetation loss (25,100 m²) overall. Hardened trails, however, resulted in more impacts to vegetation along the trail edge with low species richness, high cover of exotic grasses and few herbs, shrubs and bulbs compared to controls. Based on these results it appears that while the use of hardened trails reduces overall soil and vegetation loss, it can have more impact on vegetation along trail edges. Recommendations for more strategic trail management are presented encouraging decision-makers to more fully understand the ecological consequences of different trail types on vegetation.

Key words: trail impacts, recreational infrastructure, remnant vegetation, edge effects, fragmentation, compositional changes

Introduction

Globally, nature-based tourism and recreation is increasing (Kuenzi and McNeely 2008; Buckley 2009; Newsome et al. 2013). This includes a rise in popularity among trail-based activities such as hiking and mountain-biking (Balmford et al. 2009; Monz et al. 2010; Newsome et al. 2013). As a result, the creation of recreational trails in natural areas is becoming more common, especially in countries such as the USA and Australia (Monz et al. 2010; US National Park Service 2014; Ballantyne et al. 2014). While providing access to natural areas is important for human health and wellbeing (Swanwick et al. 2003; Lee and Maheswaran 2011) and increases support for their conservation (Spenceley et al. 2015), the infrastructure required for nature-based tourism and recreation has a range of environmental impacts (Matlack 1993; Stenhouse 2004; Godefroid and Koedam 2004; Hill and Pickering 2006; Olive and Marion 2009; Marion and Leung 2011; Ballantyne et al. 2014).

Recreational trails vary in their design, construction, maintenance and use. They can have hardened or unhardened surfaces, they can be narrow arteries or wide road-like developments, they can be formally created by land managers or informally created by users, and they can be single trails or a proliferation of dense networks (Marion and Leung 2001). Associated with the diversity of trails is variation in the severity and types of environmental impacts they have on vegetation (Godefroid and Koedam 2004; Hill and Pickering 2006; Monz et al. 2010; Ballantyne and Pickering 2015). To date, limited research has addressed the impacts of the presence of trails in contrast to use-related impacts such as trampling (Pickering et al. 2010a; Pescott and Stewart 2014).

Recreational trails can damage vegetation: (1) during their construction and maintenance, (2) from changes in abiotic conditions caused by the presence of the trail, and (3) from the use of the trail for different types of recreational activities. These impacts can occur at the direct local scale (along the trail corridor itself) and at the indirect local scale (as edge effects away from the trail), as well as cumulatively across the landscape (Brooks and Lair 2005). Impacts of trails can vary depending on the methods used in their construction and maintenance, but clearing and disturbing vegetation along the trail corridor and adjacent to the trail is common, especially where heavy machinery is used (Buckley 2004; Ledoux 2004). There are often changes in soil conditions including compaction, soil removal and introduction of new soil or other substrates to create the trail (Marion and Leung 2004; Müllerová et al. 2011). Impacts from the presence of the trail include changes in light regimes,

precipitation, wind exposure and temperature as well as altered water flow and reduced organic matter along edge gradients away from the trail (Laurance et al. 1998; Potito and Beatty 2005; Pohlman et al. 2007). Finally, the use of the trail has additional impacts such as trampling, erosion, compaction and trail widening (Hammit and Cole 1998; Cole 2004; Marion and Leung 2004; Pescott and Stewart 2014) with more intensively-used trails often having more impacts (Kutiel et al. 1999; Potito and Beatty 2005; Hamberg et al. 2008; Kim and Daigle 2012). The use of trails for poaching and vandalism as well as the spread of weeds, pathogens and feral animals is also of concern (Benninger-Truax et al. 1992; Matlack 1993; Buckley et al. 2004; Baret and Strasberg 2005; Pickering and Mount 2010).

To date, most comparative research looking at trail impacts has focused on comparing different types of use through measuring impacts of different trail-based activities (Cole and Bayfield 1993; Kutiel et al. 1999; Talbot et al. 2003; Cole 2004; Hill and Pickering 2009; Monz et al. 2010; Pickering et al. 2010a). These studies have found that the timing, type and intensity of use and the tolerance of ecosystems affect the severity and types of impacts on vegetation (Hammit and Cole 1998; Cole 2004; Marion and Leung 2004; Pickering 2010). Fewer studies have assessed impacts of the trail infrastructure itself, and only a handful have specifically compared impacts among different types of trails (Godefroid and Koedam 2004; Hill and Pickering 2006; Ballantyne and Pickering 2015).

These few studies have found that the severity of impacts on vegetation does vary among different types of trail. Formal hardened trails, for example, can change vegetation along the trail edge, often as a result of disturbance during the construction and maintenance of the trail (Godefroid and Koedam 2004; Hill and Pickering 2006; Müllerová et al. 2011; Ballantyne and Pickering 2015). This can result in the colonisation of trail edges by weeds and ruderal species (Hill and Pickering 2006), decreases in native plant cover, especially disturbance-sensitive species (Hill and Pickering 2006), changes in soil nutrients (Müllerová et al. 2011) and ultimately long-term changes to vegetation composition and structure (Hill and Pickering 2006; Malmivaara-Lämsä et al. 2008; Ballantyne and Pickering 2015). Informal, unhardened and narrow trails, can have fewer and less severe impacts on vegetation along the trail edge as there is often less disturbance during their creation, but there can be continuing impacts on the trail itself (Marion and Leung 2004; Olive and Marion 2009; Marion and Leung 2011). This includes erosion and trail widening when the surface is not stabilised by hardening (Olive and Marion 2009; Wimpey and Marion 2010).

The aim of the current research was to assess how recreational trails differ in the severity and types of impacts they have on vegetation. The research was undertaken in an endangered woodland close to a major city (Adelaide, South Australia) that is popular for a range of trail-based recreation activities including hiking and mountain biking. Specifically we: (1) mapped the extent and types of recreational trails in the woodland, (2) compared on-trail impacts between trail types (direct local scale), and (3) compared the impacts of different trail types on the composition of vegetation along the edges of the trails (indirect local scale). Based on the results of this study, we then provide recommendations for the management of different types of recreational trails more generally.

Methodology

Study Ecosystem

Our study assessed trail impacts in Grey Box grassy woodland (*Eucalyptus microcarpa*) which is listed as an endangered plant community under Australian legislation (Australian Government 2010) and as critically endangered within the World Wildlife Fund's terrestrial ecoregions database (World Wildlife Fund 2014). It is restricted to a series of scattered remnants across south-eastern Australia from central New South Wales through north and central Victoria and into South Australia (Australian Government 2010, 2012). Before European settlement the ecosystem covered around 3.4 million ha, but today occupies just over 500,000 ha; a loss of 85% (Australian Government 2010, 2012). The primary causes of this decline have been land clearing for agriculture, development and resource extraction with ongoing pressures from weed invasion, grazing and altered fire regimes (Yates and Hobbs 1997; Spooner et al. 2002; Australian Government 2010).

In South Australia, near the capital city of Adelaide (population 1.25 million people), the loss of Grey Box grassy woodland has been particularly severe declining from 20,000 ha to just 2,000 ha (90% loss) (Kraehenbuehl 1996; Paton 2008). The woodland typically occurs on undulating plains and slopes with productive soils derived from alluvial or colluvial deposits with rocky outcrops and clay pans (Australian Government 2010). Canopy cover is slightly denser than elsewhere in its range, likely as a response to higher rainfall in the region which averages 375-700 mm/year and Mediterranean temperatures (mean summer maximum 27°C; mean winter maximum 12°C) (Paton 2008; Australian Government 2012). The canopy is dominated by around 50% cover of the dominant tree *Eucalyptus microcarpa* often intermixed with stands of *E. camaldulensis* and *E. leucoxylon* (Australian Government 2010). The shrub layer provides around 30-40% cover and is dominated by species such as *Acacia pycnantha* and *Dodonaea viscosa*. The understory is highly diverse and

dominated by grasses such as *Rytidosperma caespitosum* and *Poa labillardieri* var. *labillardieri* with numerous herb, bulb, chenopod and cryptophyte species. There is also high cover of invasive European grasses such as *Avena barbata*, *Brachypodium distachyon* and *Briza major* (Australian Government 2010). Total plant species richness often exceeds 200 even in small remnants (Quarmby pers. obs.) and includes numerous nationally-threatened species such as the Pink-lipped Spider-orchid (*Caladenia behrii*) and Plum Leek-orchid (*Prasophyllum pruinatum*). The ecosystem is also a stronghold for some International Union for the Conservation of Nature (IUCN) Red-listed species such as the Swift Parrot (*Lathamus discolor*) and Flinders Ranges Worm-lizard (*Aprasia pseudopulchella*).

Study Site

The Adelaide Grey Box grassy woodland is highly fragmented and consists of numerous small remnants, the largest of which is 190 ha, with most <100 ha. Most remnants are within public reserves and private land between Adelaide and the southern Flinders Ranges (Australian Government 2010). These remnants are increasingly used for a range of recreational trail-based activities including hiking and mountain biking, including the large 167 ha of Grey Box grassy woodland within Belair National Park (835 ha) (Figure 1). This peri-urban, IUCN Category II Park is 13 km south-east of Adelaide (Figure 1). The Park was proclaimed in 1891 and underwent a period of use as a semi-formal arboretum and government residence as well as being used for recreation with the creation of tennis courts, grass ovals and picnic areas (South Australian Government 2012). Today it is managed for conservation and recreation with around 250,000 visitors per year (Department of Environment, Water and Natural Resources 2003; Mitcham City Council 2015).



Figure 1: Map of Belair National Park (thick white boundary line), south-eastern Adelaide, South Australia ($35^{\circ}01'22.70''$ S, $138^{\circ}06'84.80''$ E) showing the location of Grey Box grassy woodland remnants (highlighted patches to north-west of Belair National Park) and recreational trail networks within these remnants. All spatial data obtained from the Department of Environment, Water and Natural Resources, South Australia (DEWNR). Map created using ESRI ArcMap Version 10.1.

Data Collection

All recreational trails within the 167 ha of Grey Box grassy woodland in Belair National Park were mapped including formal and informal trails. Formal trails were those with visible maintenance, signage and/or access infrastructure and/or mapping by land-owners for public use. Informal trails were those both created and maintained by visitors for recreation and are outside of the formally-managed trail system (Leung et al. 2002). Trails were mapped using a Trimble Yuma GPS Tablet with 1-2 m real time accuracy and a recording interval of 1 m.

The formal and informal trails were further categorised based on their average width and surface using a visual survey method similar to that used in trail condition class assessments (e.g. Farrell and Marion 2001; Ballantyne et al. 2014). Average width of the trail tread, defined as the most heavily trafficked area of the trail (Wimpey and Marion 2010), was measured at the start of each new section of trail and at regular intervals 100 m along the trail. Average widths were calculated for each section and then all trails grouped into small (< 1 m), medium (1 – 3 m) and large (> 3 m) trails. Surfaces were visually assessed, with bare soil, gravel and tarmac surfaced trails all found within the woodland. As a result five trail types were identified in total: (1) small bare soil, (2) medium bare soil, (3) large bare soil, (4) medium gravel and (5) large tarmac trails. For each of the five types of trails, 10 stratified random sites were located across the combined length of each type using ET GeoWizards 10.2 in ArcMap Version 10.1 (Ballantyne et al. 2014) for more detailed sampling of the trail and vegetation.

To assess impacts on the trail surface, soil loss (cross-sectional area), trail slope alignment angle and surface compaction were measured at each of the 10 sites per trail type. Cross-sectional area and trail-slope alignment angle were used to estimate soil loss using the methodology in Olive and Marion (2009). Soil compaction was measured using a penetrometer with a maximum capacity of 4.5 kg/cm² at five equally-spaced points across the span of the trail tread at each site.

To assess the impacts of the five types of trails on vegetation adjacent to the trail, we surveyed all plants (excluding trees) in 1 x 3 m quadrats located immediately adjacent to the edge of the trail, at 5 m and at 10 m away from the trail edge at each site (total of 150 quadrats, e.g. three distances, 10 replicate sites for each of five trail types). In addition, vegetation was assessed in 1 x 3 m quadrats at each of 10 randomly-selected control sites that were a minimum of 50 m from the edge of trails, roads or the woodland edge. Field work was carried out from 20 - 31 October 2014.

In each of the 160 quadrats, total vegetation cover, cover of separate growth forms, species richness and canopy cover were recorded along with abiotic variables (see below). Vegetation cover was

measured as the top-cover (vegetation, rock, bare ground, dead wood or moss) and the total overlapping cover of all plant species intercepted by a thin metal wire placed at 100 randomly-located points within the quadrat. The number of 'hits' per species was converted into percentage cover values and used to calculate both overlapping vegetation cover and overlapping cover of separate growth forms. Total species per quadrat was used to calculate total species richness and weed richness. Canopy cover was analysed as a percentage by photographing the quadrangle of airspace directly above each zone and then calculating the number of pixel cross-hair points occupied by canopy, sky or other (Monz et al. 2010; Ballantyne and Pickering 2015).

At each site (50 trail sites + 10 controls) abiotic covariates that are likely to affect vegetation were also recorded. These included slope, altitude, aspect, soil type, distance to water and time since last fire. Slope was measured using the Hunter Research and Technology LLC Theodolite HD Version 3.2 app for iPad (available online <http://hunter.pairsite.com/theodolite/>) by aligning the top of two poles of equal height 5 m either side of the survey point and measuring the difference in angle. Altitude was measured using a 1 second SRTM-derived 3-second smoothed digital elevation model provided by the Australian Government for the Adelaide region (<http://www.ga.gov.au/data-pubs>). Aspect was measured using an electronic GPS-corrected compass bearing against true north. Distance to water was the Euclidean distance to nearest water body (stream, river, lake) using ArcMap Version 10.1. Soil type was measured using the soil landscape map units of southern South Australia map (<http://www.naturemaps.sa.gov.au/>). Time since last fire was taken from a fire management dataset recording major fires in protected areas (<http://www.naturemaps.sa.gov.au/>).

Data Analyses

The total area of each trail type, and therefore the total area of vegetation lost to the trail surface, was calculated by multiplying the total length (measured in ArcMap Version 10.1) by the average width of each type of trail. We were then able to calculate total soil loss for each trail type by multiplying average soil loss per site (cm^2) by the total length (cm^3) of that type of trail.

To analyse differences among the trail variables: average soil loss (log₁₀ transformed), trail slope alignment angle (log₁₀ transformed) and surface compaction, a series of One-way ANOVAs were conducted in SPSS Version 21 when the assumptions of normality and variance were satisfied. Least significant differences were used as post-hoc tests to determine which pairs of trails differed.

To analyse whether vegetation 10 m from the trails differed from the controls, data for these quadrats was compared with that from control quadrats using a series of One-way ANOVAs. As no significant differences were found, the control quadrats were removed from further analyses, with the 10 m quadrats treated as the 'natural' condition of the vegetation in subsequent analyses.

To assess differences in the impact of the five trail types on understory vegetation, and how far from the trail impacts could be detected, linear mixed models were used to analyse species richness, relative vegetation cover, relative weed cover (arcsine square-root transformed) and weed species richness (log transformed) in SPSS Version 21. Trail type, distance and distance*trail type were set as fixed factors, and sites (blocks) used as a random factor. Covariates (abiotic and biotic) were added to the list of fixed factors with aspect and altitude log₁₀-transformed to satisfy assumptions of normality and homoscedasticity. Covariates were added and removed sequentially to determine the most significant models according to Akaike's Information Criterion (AIC). Finally, to compare any significant effects using the most powerful model, pairwise comparisons using estimated marginal means were computed for trail type and distance using Syntax commands. If an interaction was significant, separate One-way ANOVAs were performed for each trail type and distance to understand the nature of the interaction. A p value of ≤ 0.03 was used to account for the increased chance of falsely assuming a significant difference, i.e. an increased chance of Type II errors.

To assess overall similarity of vegetation depending on how far the quadrat was from the trail and the type of trail, values for Sørensen's index were calculated using presence/absence data for all living vascular species per quadrat. A Bray-Curtis similarity matrix was used to compare composition between quadrats [site(distance*trail type)] for all trails with data being extracted and analysed using a One-way ANOVA. Tukey post-hoc tests were used to determine the nature of any significant differences.

To analyse differences in species composition and combined relative cover of growth forms between distances and trail types, a permutational multivariate ANOVA (PERMANOVA) was used with trail type, distance and distance*trail type as fixed factors, and site(trail type) as a random factor in PRIMER Version 6 using a Bray-Curtis dissimilarity matrix on square-root transformed cover data for individual species (divided by total cover) with the cover of litter, bare ground, rock, dead wood and moss removed. To determine if composition between 10 m and control sites was similar, we used a One-way ANOSIM. We found that composition was similar between these two groups of sites and so 10 m was used as the control. To show compositional differences among the five trail types and three distances, multi-dimensional scaling (MDS) plots were used to show the clustering of samples in two-dimensional space with goodness of fit shown as a stress value. This method is useful as it (1)

visually portrays patterns by clustering and ordinating samples and (2) using the PERMANOVA function, statistically analyses them with a non-parametric permutation-based test (9,999 permutations), similar to that of an ANOVA, but not requiring a normalised data distribution (Clarke 1993). Finally, a SIMPER analysis was used to determine which species contributed to any observed differences between groups.

Additionally, we used separated Linear Mixed Models on total cover of each growth form (arcsine square-root transformed) per quadrat as an independent variable for graminoids, herbs and bulbs to determine the overall strength and direction of any observed effects. Shrubs were removed as a variable as they were absent from many quadrats.

To assess whether the trails had an effect on the cover of any dominant species [occurring in at least 50% of quadrats (75 out of 150)], cover data (arcsine square-root transformed) for that species was included in separate Linear Mixed Models, using post-hoc pairwise comparisons to determine the nature of any significant differences. These species included: the native shrub *Dodonaea viscosa*, and the two exotic grasses *Briza major* and *Brachypodium distachyon*.

Results

On-trail impacts

Within the 60 sample sites in the 167 ha of Grey Box grassy woodland in Belair National Park, there was a total of 109 plant species including 4 types of trees, 11 shrubs, 20 bulbs, 49 herbs, 19 grasses, 5 sedges/rushes and 1 fern. There was also 20.1 km of trails in these woodlands, with 16.3 km formal and 3.8 km informal trails. There was approximately 2.2 km of small bare, 10.1 km of medium bare, 2 km of large bare, 1.5 km of medium gravel and 4.4 km of large tarmac trails (Table 1). The small bare earth trails were all created by users (informal), while the other four trail types were either entirely, or predominantly, trails provided and maintained by the Park management.

The five types of trails differed in average width ($F = 52.075$, $p < 0.001$), apart from medium bare and medium gravel trails ($p = 0.320$). Because of their hardened surface, the large tarmac trails had no soil loss from the surface. Small bare trails had less soil loss (135 cm^2) than the other three types ($F = 12.991$, $p < 0.001$) which all lost around 602 cm^2 of soil. Total soil loss was very high for medium bare trails, estimated at $6,821,898 \text{ m}^3$ in total, due to the greater length of this type of trail. Surprisingly, soil loss for medium gravel trails was high at $409,524 \text{ m}^3$; around 40% greater than small bare trails which were longer than the total length of medium gravel trails. Compaction ($F = 0.879$, $p = 0.484$)

and trail slope alignment angle ($F = 0.807$, $p = 0.527$) did not differ among the five types of trails (Table 1).

Because the five types of trails varied in length and width, they differed in the amount of vegetation lost. Medium bare trails were associated with the greatest loss (25,100 m²) of vegetation as they were the most extensive trail type, while large tarmac trails, which were much shorter accounted for similar levels of vegetation loss (23,800 m²) because they were wider. Small bare trails caused the least loss of vegetation (1,700 m²), in part because they were narrower. Total vegetation loss due to tall five trails was 60,712.8 m², which is around 4% of the total remnant of Grey Box grassy woodland.

Table 1: Means and standard deviations for different trail variables for each of the five trail types assessed in Grey Box grassy woodland in Belair National Park. Significant differences indicated in bold ($p < 0.05$) according to One-way ANOVA with lettering showing the nature of the difference according to least significant difference post-hoc comparisons (e.g. 'a' is significantly different to 'b' but the same as 'a'). TSAA = trail slope alignment angle.

	Small bare	Medium bare	Large bare	Medium gravel	Large tarmac	Totals
Length trails (m)	2,157.6	10,052.9	2,011.7	1,457.9	4,398.5	20,078.6
Area trails (m ²)	1,726.1	25,132.3	7,040.9	3,061.6	23,751.9	60,712.8
Surfacing	Unsurfaced	Unsurfaced	Unsurfaced	Dolomite gravel	Bitumen	
% Formal	0	90	70	100	100	
% Informal	100	10	30	0	0	
Av. width (m)	0.8 ± 0.3^a	2.5 ± 0.7^b	3.5 ± 1.2^c	2.1 ± 0.6^b	5.4 ± 0.6^d	
Av. soil loss (cm ²)	134.8 ± 148.5^a	678.6 ± 578.5^b	845.1 ± 831.9^b	280.9 ± 181.4^b	0	
Total soil loss (m ³)	290,844.5	6,821,897.9	1,700,087.7	409,524.1	0	
Av. compaction (kg/cm ²)	4.2 ± 0.5	4.3 ± 0.5	4.4 ± 0.3	4.4 ± 0.2	> 4.5	
TSAA (°)	44.5 ± 23.1	37.5 ± 27.8	55.5 ± 29.5	34.5 ± 36.1	39.5 ± 26.8	
Predominant use	Hiking	Hiking, mountain biking	Hiking, mountain biking	Hiking, mountain biking	Driving, hiking	

Was there an effect of the trails on vegetation?

There were no significant differences in any of the dependent variables between the control quadrats (50 m from trails) and those 10 m from the trails except for cover of herbs, indicating that most effects of the trails were limited to vegetation < 10 m from the trails. Vegetation in the control and 10 m quadrats was characterised by high cover of the native sub-shrubs *Hibbertia exutiacies* and *Hibbertia australis* (23% cover) and graminoids composed largely of the exotic grasses *Briza major* (18%) and *Brachypodium distachyon* (11%) along with the native sedge *Lepidosperma curtisiae* (18%) and tussock grass *Rytidosperma caespitosa* (10%). The native bulbs *Arthropodium strictum* (5%) and *Lomandra multiflora* (5%) and the exotic herb *Plantago lanceolata* (11%) also had comparatively high cover.

Vegetation was affected by the trails, with significant differences in several variables between quadrats on the edge of trails and those 5 m and 10 m away from the trails. For all five trail types, there was less vegetation in quadrats on the edge of trails (43% ± 28; $F = 15.534$, $p = < 0.001$) compared to quadrats 5 m (62% ± 25, $p = 0.001$) and 10 m (63% ± 23, $p = < 0.001$) away, but no differences between the 5 m and 10 m quadrats ($p = 0.864$) (Tables 2 and 3). Bulb cover was also affected by trails ($F = 11.843$, $p < 0.001$), with reduced cover near the trail (Tables 2 and 3). There were no overall effect of trails on the cover of dominant species including the native shrub *Dodonaea viscosa*, and the two exotic grasses *Briza major* and *Brachypodium distachyon*.

Overall composition (based on the ANOSIM) differed with distance from trails, but was also affected by an interaction with trail type (see below). The cover of different growth forms was affected by the trails (Global Rho = 0.26, $p < 0.001$, Stress = 0.18) with an increase in the cover of shrubs and bulbs in quadrats 5 m and 10 m (18.4% and 20.9%) from the trail compared to those on the trail edge (11.8%). There was a slight decrease in the cover of graminoids for the 5 m and 10 m quadrats (49.7% and 47.6%) compared to the trail edge (55.6%). These patterns were in part due to decreasing cover of the exotic grasses *B. major* and *B. distachyon* further from the trail and a rise in the cover of native grasses such as *Rytidosperma caespitosa* and *Microlaena stipoides* var. *stipoides*. Vegetation on the edge of the trails was typically dominated by grasses (average cover 71%) with lower cover of sedges (7%), shrubs (8%) and bulbs (<1%). Vegetation in quadrats 5 m from the trails was also dominated by grasses (60%) but with higher cover of shrubs (13%), sedges (9%) and mostly exotic bulbs (5%). Vegetation in quadrats 10 m from the trails was dominated by grasses (53%) but > 20% of them were native, and there was a higher cover of shrubs (15%), sedges (10%) and native bulbs (7%).

Although there were 39 species of weeds (1 shrub, 8 bulbs, 11 grasses, 19 herbs) recorded across the 160 quadrats surveyed, with average weed cover of 29% per quadrat, there was no effect of the trails on weed cover *per se* (Tables 2 and 3).

Table 2: Results from Linear Mixed Models (LMM) and PERMANOVA analyses of vegetation in quadrats at different distances from five types of trails. Significant differences indicated in bold ($p < 0.05$). Neg. = negative.

Dependent Variable	Trail type	Distance from trail	Interaction	Significant covariates
Species richness (LMM)				
All	F = 1.264 p = 0.297	F = 10.746 p = <0.001	F = 2.590 p = 0.013	
Weeds	F = 1.187 p = 0.329	F = 0.881 p = 0.418	F = 0.655 p = 0.729	Altitude neg. interaction F = 5.954, p = 0.019
Total % overlapping cover (LMM)				
Vegetation	F = 1.140 p = 0.350	F = 15.675 p = <0.001	F = 1.195 p = 0.311	
Weeds	F = 1.204 p = 0.323	F = 0.561 p = 0.573	F = 1.030 p = 0.422	Altitude neg. interaction F = 5.469, p = 0.023
Graminoid	F = 0.611 p = 0.656	F = 1.475 p = 0.234	F = 0.454 p = 0.885	
Herb	F = 2.558 p = 0.049	F = 2.902 p = 0.060	F = 0.715 p = 0.678	
Bulb	F = 0.529 p = 0.715	F = 11.843 p = <0.001	F = 1.341 p = 0.233	
Overlapping cover of dominant species				
<i>Dodonaea viscosa</i>	F = 0.062 p = 0.993	F = 3.007 p = 0.054	F = 0.614 p = 0.764	
<i>Briza major</i>	F = 2.654 p = 0.045	F = 2.062 p = 0.133	F = 2.071 p = 0.050	
<i>Brachypodium distachyon</i>	F = 0.863 p = 0.493	F = 0.311 p = 0.733	F = 0.753 p = 0.644	
Composition (PERMANOVA)				
All species	Pseudo-F = 1.111 p = 0.230	Pseudo-F = 2.363 p = 0.002	Pseudo-F = 1.274 p = 0.040	
Growth forms	Pseudo-F = 1.054 p = 0.398	Pseudo-F = 5.824 p = <0.001	Pseudo-F = 1.112 P = 0.314	
Sørensen Similarity Index	n/a	n/a	F = 4.564 p = 0.004	

Table 3: Characteristics of vegetation in quadrats for controls vs 10 m, and for quadrats on the edge of the five trail types. Significant differences indicated in bold ($p < 0.05$) according to linear mixed models with lettering showing the nature of the difference according to least significant difference post-hoc comparisons (e.g. 'a' is significantly different to 'b' but the same as 'a'). Inter. = interaction term.

	Controls + 10m	Small bare edge	Medium bare edge	Large bare edge	Medium gravel edge	Large tarmac edge	Interaction or Main Effect?
Species richness	9.6 ± 2.7 a	7.6 ± 2.9 b	8.0 ± 3.3 b	6.3 ± 2.4 c	6.8 ± 3.1 b	4.1 ± 2.3 c	Interaction
Total % overlapping cover							
Vegetation	80.9 ± 21.3 a	39.3 ± 23.3 b	42.4 ± 27.2 b	34.7 ± 14.9 b	45.4 ± 30.2 b	25.0 ± 14.2 b	Main
Graminoids	36.3 ± 20.9	26.7 ± 20.9	30.5 ± 30.1	17.9 ± 10.4	35.1 ± 33.0	20.1 ± 11.4	None
Herbs	33.2 ± 16.9 a	18.6 ± 17.4 a	9.0 ± 10.1 a	12.5 ± 8.7 a	12.2 ± 12.2 a	3.6 ± 5.0 b	Main
Bulbs	7.1 ± 6.2 a	4.8 ± 5.6 b	6.1 ± 6.4 b	1.9 ± 1.4 b	2.3 ± 2.8 b	1.1 ± 2.2 b	Main
Shrubs	2.7 ± 2.2 a	3.4 ± 3.6 a	3.9 ± 5.3 a	2.5 ± 4.1 a	4.5 ± 12.1 a	0.2 ± 0.4 b	Interaction
Overlapping cover of dominant species							
<i>Dodonaea viscosa</i>	0.6 ± 1.3	2.8 ± 3.6	3.3 ± 5.3	2.0 ± 4.1	1.7 ± 4.1	0.2 ± 0.4	None
<i>Brachypodium distachyon</i>	5.5 ± 8.3	4.1 ± 5.6	8.4 ± 19.7	3.9 ± 7.3	6.1 ± 9.7	11.8 ± 9.8	None
<i>Briza major</i>	Controls	Small bare edge	Medium bare edge	Large bare edge	Medium gravel edge	Large tarmac edge	} Inter.
	16.9 ± 17.5 a	10.6 ± 16.6 a	9.4 ± 15.1 a	4.1 ± 5.3 b	5.4 ± 7.7 b	0.8 ± 1.5 c	
		Small bare 5m	Medium bare 5m	Large bare 5m	Medium gravel 5m	Large tarmac 5m	
		11.5 ± 18.1 ab	14.4 ± 15.8 a	2.7 ± 3.8 c	5.4 ± 7.7 b	2.5 ± 4.9 c	
		Small bare 10m	Medium bare 10m	Large bare 10m	Medium gravel 10m	Large tarmac 10m	} Inter.
		15.7 ± 19.1 a	7.9 ± 10.0 ab	0.4 ± 0.9 b	15.9 ± 18.2 ac	5.5 ± 9.4 abc	
Sørensen Similarity Index (%)	n/a	Small bare	Medium bare	Large bare	Medium gravel	Large tarmac	} Inter.
Edge vs. 5m composition		58.2 ± 16.3	44.9 ± 11.5	43.7 ± 22.5	50.2 ± 25.9	29.4 ± 25.7	
Edge vs. 10m composition		49.9 ± 25.4 a	37.9 ± 12.7 ab	39.4 ± 17.8 ab	49.9 ± 11.6 a	20.7 ± 17.6 b	
5m vs. 10m composition		55.8 ± 13	54.3 ± 15.1	47.1 ± 13.8	57.7 ± 11.2	52.9 ± 12.5	

Was there a difference in impacts among trail types?

Some trail impacts were not simply a result of the presence of any type of trail, but varied among the trails. This included impacts on species richness and composition (Tables 2 and 3; Figure 2). Species richness was affected by an interaction between trail type and distance (Linear Mixed Model, $F = 2.207$, $p = 0.034$), as was composition (PERMANOVA, Pseudo- $F = 1.27$, $p = 0.04$, Stress = 0.23).

For the larger trails, species richness and composition were affected by distance from the trail, but there was no effect of distance for the small and medium bare earth trails (Table 2, Figure 2). For the large tarmac trail, for example, quadrats on the edge of the trail had less than half the number of species as those further away (edge = 4.1 ± 2.3 ; 5 m = 6.8 ± 1.5 ; 10 m = 9.1 ± 2.6 ; $p < 0.021$). The vegetation in quadrats on the edge of the large tarmac trail also differed in composition to those further away with more exotic grasses such as *B. distachyon*, *B. major* and *Avena barbata* close to the trail, but fewer native grasses such as *M. stipoides* var. *stipoides*, *Anthosachne scabra* and *Poa labillardieri* which were mainly found in quadrats 5 m and 10 m away from the trail.

For the large bare trail there were also fewer species in quadrats on the edge of the trail (6.3 ± 2.4), than in quadrats 5 m and 10 m away (8.9 ± 3.1 ; 8.1 ± 2.1 , respectively; $p < 0.001$). Composition, however, was more similar (Figure 2) with a greater abundance of native sedges and graminoids (*L. curtisiae* and *R. caespitosa*) and moderate abundance of exotic grasses (*B. distachyon* and *B. major*) across all distances, but with more herb species further from the trails. For medium gravel trails, composition steadily changed from quadrats on the trail edge to those 10 m away with a steady decrease in exotic grasses (*B. distachyon* and *B. major*) and an increase in sub-shrubs (e.g. *H. australis*) and bulbs (e.g. *Arthropodium strictum*).

Average similarity in composition based on Sørensen's indices between pairs of quadrats was affected by an interaction between trail type and distance with less similarity between quadrats on the edge of trails and those 10 m away ($39.6\% \pm 20.1$ similarity; $F = 4.564$, $p = 0.004$). The greatest differences in composition were along large tarmac trails where quadrats on the edge of the trail were very different to those 10 m away ($20.7\% \pm 17.6$ similarity). Along medium and large bare trails, similarity was greater between edge and 10 m distances ($38.6\% \pm 15.2$) and along small bare and medium gravel trails, similarity was even higher ($49.5\% \pm 18.5$). Along all trails, composition 5 m from the trail was similar to edge quadrats (av. $45.3\% \pm 22.4$ similarity; $F = 2.490$, $p = 0.056$) and even more similar to 10 m quadrats (av. $53.6\% \pm 13.1$ similarity; $F = 0.925$, $p = 0.458$), and therefore acted as a transition zone.

Herb cover was lower along large tarmac trails, but this effect occurred irrespective of distance from the trail ($F = 2.558$, $p = 0.049$). Also, the 10 m quadrats for the large tarmac trails differed from the control quadrats indicating either site-specific covariation or that the impact of this trail type on herbs extends beyond 10 m from the edge of the trail.

The cover of one dominant, *B. major*, was affected by an interaction between trail type and distance, with a slight reduction in cover for quadrats along the edge of large bare, medium gravel and large tarmac trails ($F = 2.071$, $p = 0.05$) compared to other trails and controls ($16.9\% \pm 17.5$). Along the edge of the large bare trails, this species had low cover ($4.1\% \pm 5.3$), but it was even lower in quadrats further from the trail (5 m = $2.7\% \pm 3.8$; 10 m = $0.4\% \pm 0.9$). In quadrats along medium gravel and large tarmac trails, cover of *B. major* increased with increasing distance from the trail (edge = $3.1\% \pm 4.6$; 5 m = $3.9\% \pm 6.3$; 10 m = $10.7\% \pm 13.8$; Table 3).

Abiotic covariates had limited effect on vegetation with altitude having a negative linear interaction with weed species richness ($F = 5.954$, $p = 0.019$) and with weed cover ($F = 5.469$, $p = 0.023$). Slope, aspect, distance to water, soil type, time since last fire, and canopy cover had no significant effect on vegetation.

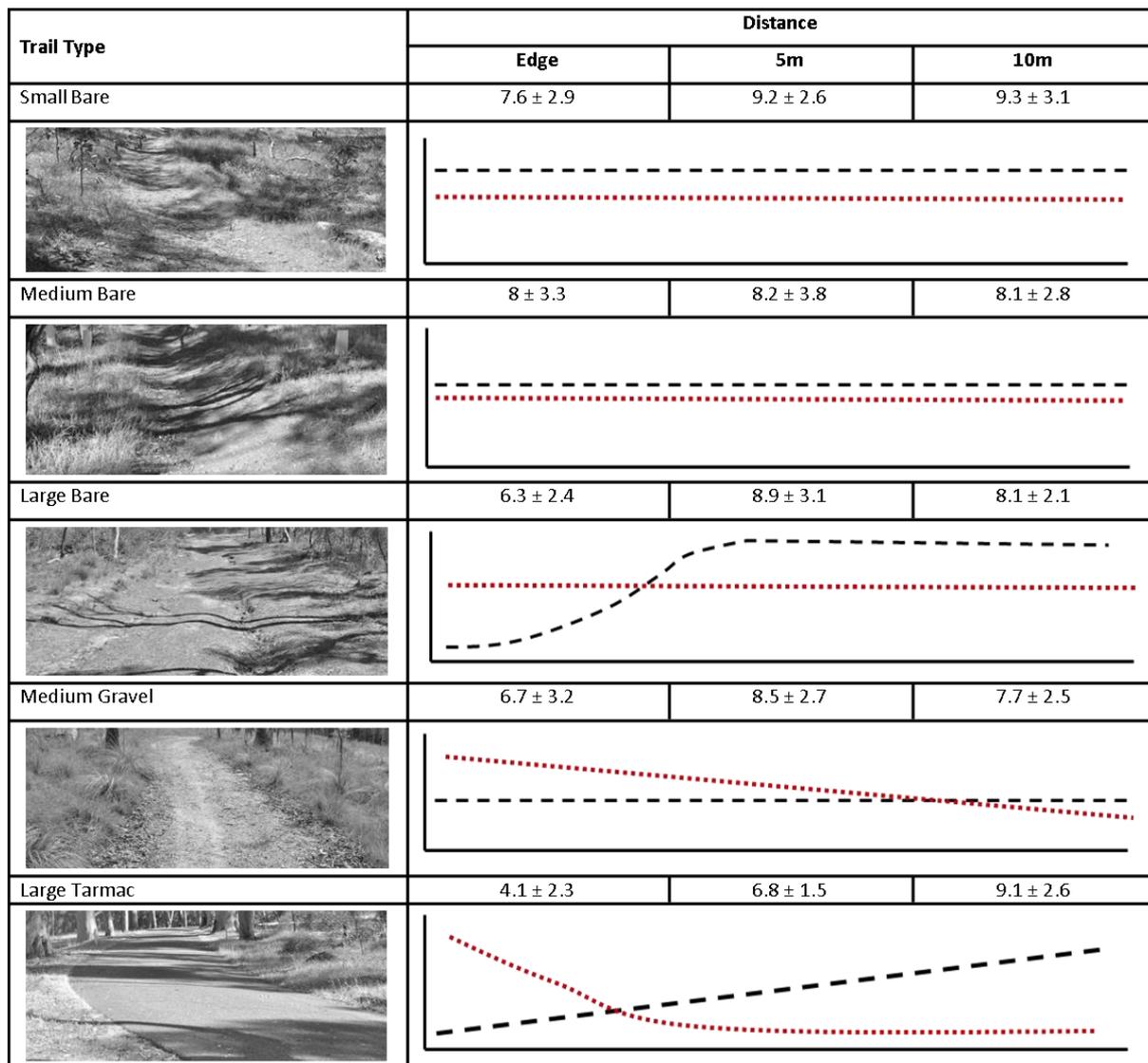


Figure 2: Effect of five different types of trails on species richness and vegetation composition in Grey Box grassy woodland. Lines signify changes in species richness (large dashed line) and species composition (small dotted line) adjacent the edge, 5 m and 10 m from the edge of the trail and among the five trail types. Species richness values for each distance are given above each graph while the line for species composition symbolises the nature of the change without respect to denominative changes in variables.

Discussion

The five types of recreational trails differed in their impacts on vegetation in the endangered Grey Box grassy woodland in Belair National Park. Remnants such as this one are important for recreational opportunities, but are also of high conservation value. A common problem for those managing this and other Parks, is which type of trails are best to minimise environmental impacts while also providing appropriate recreational opportunities. Part of this challenge has been the limited research comparing environmental impacts among different types of trails.

There is an extensive network of recreational trails in Grey Box grassy woodland

There were over 20 km of recreational trails in the Grey Box grassy woodland of which nearly 90% were formal, management-created trails. The most common of these were medium bare earth trails (60%), which collectively resulted in the loss of > 25,000 m² of vegetation. This was partly due to the total length of this type of trail in the woodland, but also due to the tendency of unsurfaced trails to widen over time (Olive and Marion 2009; Monz et al. 2010; Wimpey and Marion 2010). Other trails such as the large tarmac trails, although less common (25%) in the woodland, also resulted in the loss of > 23,000 m² of vegetation as they were wider (often > 7 m) to accommodate recreational vehicles. The width of these trails exposes vegetation on the trail edge to a range of changes in abiotic conditions such as increased wind-blow which may further reduce tree numbers and canopy cover.

Interestingly, in Belair National Park, only 11% of trails were informal, user-created trails. This may be due in part to the closure of several informal trails in the Park in the past, as part of upgrades to the trail network (Taylor Cullity Lethlean 2009). In other remnants of the same woodland in the region, there were more narrow informal trails (Ballantyne and Treby 2015). Narrow informal trails can be important components of trail systems including in protected areas (Leung et al. 2011; Ballantyne et al. 2014; Ballantyne and Treby 2015). They can result in extensive loss of habitat (up to 20%), habitat fragmentation and complex internal networks of disturbance disrupting the once-contiguous ecosystems (Ballantyne et al. 2014). The resulting impacts from uncontrolled trail networks are complex and hard to manage (Leung et al. 2011; Leung et al. 2012; Pickering et al. 2012) highlighting the importance of limiting the spread of informal trail networks particularly in areas of high conservation value (Leung et al. 2012; Wimpey and Marion 2011).

All five trails affected vegetation adjacent to the trails

All five trails had some impacts on vegetation in the Grey Box grassy woodland. This included reduced vegetation cover along the edge of the trails and up to 5 m away, but also the reduced cover of bulbs and shrubs and increased cover of graminoids. These changes are likely to be the result of: (1) trampling damage along the edge of the trail by predominantly hikers and mountain-bikers, (2) trail maintenance activities (e.g. herbicide spraying, slashing and digging), and (3) changes in abiotic conditions caused by the presence of the trail itself. Abiotic changes could include drier soils compared to vegetated areas, greater convection and conduction of heat, and reductions in local atmospheric moisture (Delgado et al., 2007). Additionally, the open nature of the trail corridors could lead to increased wind-blow damaging vegetation along the edge of the trail, especially trees and shrubs (Laurance et al. 1998; Harper and MacDonald 2002; Delgado et al. 2007; Ballantyne and Pickering 2015).

For the Grey Box grassy woodland, it appears there are already many species with traits able to deal with conditions common along the edges of trails, particularly exotic grasses that are native to the European-Mediterranean region. These species often accumulate dead matter with age, have vertical, recurved leaves and late-spring abscisic acid-accumulation which increases their capacity to deal with exposed hot conditions (Diemer 1996; Körner 2003; Volaire et al. 2009). Species native to the Grey Box grassy woodland, such as sclerophyllous shrubs and sub-shrubs (e.g. *Hibbertia* spp.) may also be well adapted to hotter, drier and windier conditions, but like many other sclerophyllous species, are less tolerant of trampling damage (Rickard et al. 1994; Bernhardt-Römermann et al. 2011; Pescott and Stewart 2014).

Trails differ in their impacts with more on-trail issues from unhardened informal trails

When impacts were compared among trails, we found strong contrasts. Conditions on the trail were generally poorest for bare trails while hardened trails were in good condition, as would be expected. Bare trails varied in width ranging from 0.8 - 4 m, and for the wider trails, soil loss was high. Cumulatively, bare earth trails accounted for 95% of total soil loss from trails in the woodland (> 8,800,000 m³). This again illustrates how unhardened trails can be prone to on-trail degradation (e.g. erosion) (Olive and Marion 2009; Wimpey and Marion 2010; Pickering et al. 2010b) including over time (Marion and Leung 2004).

In contrast, bare trails, were narrow (e.g. informal narrow bare earth trails < 1 m), with limited soil loss and on-trail conditions were as good as, or even better than, some hardened trails. Indeed, the average soil loss from medium gravel trails was 52% higher than from small bare earth trails despite

there being more small bare trails in the woodland. Maintaining such narrow trails through use of education, low gradients, grade reversals and drainage points, strategically placed pass-points and anchor points, could be an efficient and cost-effective way of maintaining on-trail conditions. These methods, however, have had limited success in the past (Olive and Marion 2009) and the apparently 'good' condition of the narrow bare earth trails in the Grey Box grassy woodland may be because these trails are relatively recent (Taylor Cullity Lethlean 2009).

For vegetation adjacent to trails, there were more impacts from wider hardened trails

When comparing impacts on vegetation adjacent to the trails, we found that larger and hardened trails had more severe impacts that extended further from the trails than smaller bare trails. While trail-hardening can be a popular management option to improve on-trail conditions (Wimpey and Marion 2010; Pickering et al. 2010b; Leung et al. 2011), and can maintain sustainable trail networks (Hill and Pickering 2006; Cahill et al. 2008; Tomczyk 2011; Zhang et al. 2012), they often dramatically alter vegetation composition along the trail edge (Godefroid and Koedam 2004; Hill and Pickering 2006; Müllerová et al. 2011; Ballantyne and Pickering 2015) and, in some cases, negatively affect visitor experiences (Cahill et al. 2008).

Vegetation along the edge of large tarmac trails contained far fewer species, was dominated by exotic grasses (*Brachypodium distachyon* and *Avena barbata*) and had less herb cover than control quadrats in the woodland. The construction and maintenance of these trails often damages vegetation along the edge of the trail, including during the use of equipment, in the introduction of materials, grading, levelling and laying of heated tarmac and the use of multiple chemical additives and finishers (Buckley 2004; Delgado et al. 2007). This can damage shrubs and trees in, and close to, the work zone which often exceeds 20 m either side of the actual trail tread (Ballantyne pers. obs.). Once laid, wide tarmac trails often have low albedo and so heat up rapidly, creating localized wind vortices resulting in drier conditions near the trails (Delgado et al. 2007; Pohlman et al. 2007). These effects may account for why much of the vegetation close to the tarmac trails in the Grey Box grassy woodland consisted of disturbance-tolerant species close (< 5 m) to the trail.

For medium gravel trails, there was a more gradual decline in the cover of exotic grasses and increases in native bulbs and shrubs away from the trail. This wider, but less severe, edge effect may be due to the substrates on the trails. The base-rich dolomite gravel used for these types of gravel trails can spread into adjacent vegetation and may leach alkalis into an otherwise base-poor environment through surface-flow (Quarmby pers. obs.). In other regions with base-poor soils, the

use of foreign alkali gravel has had a dramatic effect on species richness and composition that extends beyond 10 m from the edge of the trail, particularly down-slope of the trail due to changes in soil nutrients (Godefroid and Koedam 2004; Müllerová et al. 2011). Less disturbance during installation, but gradual leaching from gravel trails may explain why their edge effect on composition was wider, but less severe in the Grey Box grassy woodland.

Large bare trails (average width 3.5 m) also resulted in fewer species close to the trail in the Grey Box grassy woodland. Wider trails that require the removal of canopy vegetation expose the ground surface along and adjacent to the trail to greater insolation, convection and conduction resulting in drier conditions (Pohlman et al. 2007). The composition of vegetation along the edge of the large bare trails in the Grey Box grassy woodland, however, was generally similar to controls with a more even composition of exotic vs. native graminoids and more herbs. In particular, the cover of *Briza major* was low on the edge of large bare trails and continued to decrease with distance in contrast to tarmac and gravel trails where it increased positively with distance from those trails. There may have been less disturbance in the creation of the large bare trails (largely just clearing) compared to the larger hardened trails, allowing the retention of complex native edge structure, nutrient levels and soil condition, reducing the dominance of weeds close to the trail edge (Ballantyne and Pickering 2015).

Management Recommendations

This research demonstrates that recreational trails differ in their severity and types of impacts caused to vegetation, and so future management of natural areas must account for this variation when developing sustainable trail networks. The results support the use of hardened trails along the most intensely-used areas, on steep slopes or in areas inappropriate for unhardened trails (e.g. riparian areas) where there is a risk of deteriorating on-trail conditions and trail widening. Hardening may also help restrict the creation of informal trails networks (Marion and Leung 2011; Wimpey and Marion 2011; Leung et al. 2012). Hardened trails, however, do have local impacts on edge vegetation and so their use should be limited, where possible, in areas of high conservation value, such as in Grey Box grassy woodlands. The use of wide tarmac trails for vehicle access and base-rich substrates such as dolomite gravel should be avoided because they appear to have had the greatest effects on plant composition appearing to favour novel disturbance-tolerant species $\geq 10\text{m}$ from the trail edges. Minimising damage during construction, using locally-sourced surfacing substrates and actively rehabilitating edge vegetation may help mitigate some of these impacts (Ballantyne and Pickering 2015).

The results indicate that, where unhardened trails are strategically-located and maintained, they can both sustain good on-trail conditions and have limited effect on edge vegetation. This is especially important in areas of high conservation value containing disturbance-sensitive species. As long as unhardened trails are not developed in topographically-sensitive areas such as over soils prone to water-logging, deep or Aeolian soils, steep slopes and riparian zones, trail gradients are kept to a minimum and trails are placed parallel to contour lines with adequate drainage systems, they can remain in good condition over time (Marion and Leung 2004). Maintaining the trail in good condition can be difficult with high use, if it results in vegetation loss, soil erosion and trail widening. These type of issues with unhardened trails can be minimised by using natural anchor points (rocks and logs), strategically-placed pass points and by actively managing for different types and intensities of use. Finally, monitoring how trails affect vegetation and soils, as well as fauna and aquatic systems, and how their use changes over time is important for long-term trail sustainability.

Conclusion

We compared the types and severity of impacts by five types of recreational trails on vegetation in an endangered woodland. These types of ecosystems are undergoing increasing loss and degradation globally due to urbanisation and clearing with the development of recreational trails adding to these threats. We found trails varied in their impacts. Larger unhardened bare earth trails caused the most soil and vegetation loss, while hardened trails were less common and so resulted in less overall damage. However, hardened trails had the greatest effect on vegetation along the edge of the trail including decreased species richness, altered composition and a decreases in sensitive plant species. It is likely that these changes in vegetation are a result of disturbance during the construction and maintenance of the trails. Based on the results of the current study, and the few others comparing different types of trails, we suggest a mixed management approach may be best, that involves hardening trails in popular areas, but with minimal disturbance during construction, the use of local materials where possible and vegetation rehabilitation once built. In less popular areas and/or those of particularly high biodiversity and conservation value such as Grey Box grassy woodland, leaving trails unhardened but investing effort into more strategic trail placement and sustainable trail design may help maintain on-trail conditions and limit the spread of informal trails. These broad recommendations will help assist natural area managers to more effectively account for both recreation and conservation demands, which is of particular importance in already threatened ecosystems such as Grey Box grassy woodland.

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Chapter 6. Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure

The previous chapter compared the effect of five different types of recreational trails on vegetation along the trail edges in an endangered Grey Box grassy woodland remnant. It found that while hardened trail types such as gravel and tarmac often reduced the extent of on-trail degradation such as erosion, they had greater impacts on vegetation along their edges. Hardened trails caused altered composition, reduced cover, increasing weed graminoids and reduced herbs, bulbs and shrubs up to 10m from the trail edge.

The literature review (Chapter 2) also showed that little research has been done on the impacts of recreational trails on the structure of plant communities. This next chapter advances on this research by addressing the impacts of trails on the loss of, and structural changes in, endangered Tall Open Blackbutt forest remnants, and compares these effects between seven different types of formal (management-created) and informal (user-created) trails.

This chapter consists of the published version of a paper co-authored with my principle supervisor. The bibliographic details of the paper, including all authors, are:

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My contribution to the paper involved: field-work logistics, most of the field-work, data collection, data analyses, drafting the manuscript, producing maps, tables and figures and submission to the journal.



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Research article

Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure



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ABSTRACT

Recreational trails are one of the most common types of infrastructure used for nature-based activities such as hiking and mountain biking worldwide. Depending on their design, location, construction, maintenance and use, these trails differ in their environmental impacts. There are few studies, however, comparing the impacts of different trail types including between formal management-created trails and informal visitor-created trails. Although both types of trails can be found in remote natural areas, dense networks of them often occur in forests close to cities where they experience intense visitor use. To assess the relative impacts of different recreational trails in urban forests, we compared the condition of the trail surface, loss of forest strata and changes in tree structure caused by seven types of trails (total network 46.1 km) traversing 17 remnants of an endangered urban forest in Australia. After mapping and classifying all trails, we assessed their impact on the forest condition at 125 sites (15 sites per trail type, plus 15 control sites within undisturbed forest). On the trail sites, the condition of the trail surface, distance from the trail edge to four forest strata (litter, understory, midstorey and tree cover) and structure of the tree-line were assessed. Informal trails generally had poorer surface conditions and were poorly-designed and located. Per site, formal and informal trails resulted in similar loss of forest strata, with wider trails resulting in greater loss of forest. Because there were more informal trails, however, they accounted for the greatest cumulative forest loss. Structural impacts varied, with the widest informal trails and all formal hardened trails resulting in similar reductions in canopy cover and tree density but an increase in saplings. These structural impacts are likely a function of the unregulated and intense use of large informal trails, and disturbance from the construction and maintenance of formal trails. The results demonstrate that different types of recreational trails vary in the type and range of impacts they cause to forests. They highlight the importance of careful consideration towards management options when dealing with trail networks especially in areas of high conservation value.

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Chapter 7. Recreational trails are an important cause of fragmentation in endangered urban forests: a case-study from Australia

The previous chapter looked at the total loss of vegetation and impacts to tree structure along the edges of seven different types of formal and informal recreational trails in endangered Tall Open Blackbutt forest remnants. It found that similarly to Chapter 5, formal, hardened trail types reduce on-trail degradation but their impacts on vegetation on the edge of trails is far greater than unsurfaced trails. This included reductions in the density of mature trees, loss of canopy cover and increases in sapling abundance.

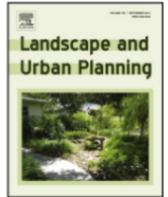
The literature review (Chapter 2) highlighted knowledge gaps on the impacts of recreational trails at a cumulative landscape scale, especially in terms of vegetation loss and fragmentation. Therefore, this next chapter assesses the extent and possible causes of fragmentation by recreational trails within endangered Tall Open Blackbutt forests.

This chapter consists of the published version of a paper co-authored with my principle supervisor and my associate supervisor. The bibliographic details of the paper, including all authors, are:

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Key images from this manuscript were also used as the cover image for Landscape and Urban Planning Volume 130 (2014) including a short written description of the work on the cover inset.

My contribution to the paper involved: field-work logistics, most of the field-work, data collection, data analyses including spatial analyses, photography, drafting the manuscript, production of tables and figures and submission to the journal.



Research Paper

Recreational trails are an important cause of fragmentation in endangered urban forests: A case-study from Australia



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HIGHLIGHTS

- Over 5.7% of 829 ha of endangered forest was lost to 46.1 km of recreational trails and their edge effects.
- Fourteen different trail types contributed to this loss most of which were narrow informal bare earth trails.
- The amount of forest lost to trails approaches that of recent urban development.
- In urban remnants with numerous entry points, fragmentation was higher.
- Recreational trails, particularly those unregulated, contribute significantly to the loss and fragmentation of endangered forest remnants.

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ABSTRACT

Remnant urban forests are often popular sites for recreational activities such as hiking, biking and motorised recreation. This can result in the formation of extensive trail networks, fragmenting vegetation into patches separated by modified edge effects and ultimately contributing to the degradation of the ecosystem as a whole. Here we use a GIS approach to assess the extent and diversity of trail-based fragmentation across 17 remnants of endangered urban forest (total area 829 ha, Tall Open Blackbutt Forest) in southeast Queensland, Australia. Fourteen different trail types totalling 46.1 km were mapped with informal biking and hiking trails the most common (57%, 26.5 km). More than 47 ha (5.7%) of forest have been lost to trails and their edge effect, nearly equal to the area recently cleared for urban development. The degree of fragmentation in some remnants was in the same order of magnitude as found for some of the most popular nature-based recreation sites in the world. In localised areas, the fragmentation was particularly severe as a result of wide trails used by motorised recreation, but these trails were generally uncommon across the landscape (5%). Spatial regression revealed that the number of access points per remnant was positively correlated with the degree of fragmentation. We encourage more landscape-scale research into trail-based fragmentation due to its capacity to impact extensive areas of endangered ecosystems. Management should seek to minimise the creation of informal trails by hardening popular routes, instigating stakeholder collaboration and centralising visitor flow.

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Chapter 8. General discussion

8.1 Introduction

Nature-based tourism and recreation is increasing globally and has multiple social, economic and environmental benefits and impacts (World Health Organisation, 2005; Maller et al., 2009; WTTC, 2015). Many of the most popular nature-based activities use recreational trails to access natural areas including hiking and mountain-biking (Nvight, 1996; Cordell and Herbert, 2002; Queensland Government, 2007; Cordell et al., 2008; Balmford et al., 2009; Olive and Marion, 2009). As a result there is an increasing spread of recreational trails in natural areas (Leung and Marion, 2000). To date research assessing the impacts of recreational trails on vegetation and soils has focused largely on use-related compositional impacts and on-trail degradation at a local scale with other impacts currently poorly understood (Chapter 2). This lack of knowledge is of particular concern for recreational trails in threatened plant communities (Newsome and Davies, 2009; Ballantyne and Pickering, 2012).

This thesis addresses knowledge gaps surrounding trail impacts on vegetation including in threatened plant communities. Impacts were assessed in three communities: (1) an alpine shrub-dominated community in Kosciuszko National Park, New South Wales, due to be listed as critically endangered by the New South Wales Government (2), a Mediterranean-climate grassy woodland in the peri-urban Belair National Park in South Australia listed as endangered by the Australian Government and (3) peri-urban subtropical open forest remnants in south-eastern Queensland listed as endangered by the Queensland Government. A range of analytical methods were used in this study including GPS mapping, GIS spatial analyses, functional traits analyses, regressions, linear mixed modelling, parametric and non-parametric testing, time-series data and ordinations.

The results of this thesis demonstrate that recreational trail infrastructures have a range of significant impacts on threatened plant communities, and plant communities more generally. These include impacts at all spatial scales including direct local to the trail surface itself (vegetation loss, soil loss, compaction), indirect local to vegetation along the trail edges (reduced tree density, increased saplings, altered composition, reduced vegetation cover, weeds) and cumulatively across the landscape (cumulative loss of vegetation and soil, fragmentation). Impacts also include changes in composition (changing species richness, altered composition, changing dominance, weed cover), structure (reduced tree density, increasing saplings, soil loss, canopy loss) and function (reduced facilitation) in the communities studied. Impacts also varied in type and severity among different trail types with unhardened, informal trails causing vegetation and soil loss, fragmentation and

overall remnant reduction, but hardened formal trails contributing more to changes to vegetation along trail edges.

The following sections discuss in more detail the key results of the research in relation to the thesis aims (which are restated as sub-titles 8.2 to 8.6). The final section summarises the research contributions to knowledge, implications for the management of recreational trails, specific implications for the communities studied and future research directions on the impacts of recreational trails to vegetation with a focus on threatened plant communities.

8.2 What is the current state of research on trail impacts on vegetation and soils?

A global systematic quantitative literature review of peer-reviewed original research papers (Chapter 2) documented important trends in what has, and has not, been studied on the impacts of recreational trails on vegetation and soils. The results showed that although there are increasing numbers of papers assessing trail infrastructure impacts, the literature is limited compared to that on use-related impacts such as trampling (e.g. Pescott and Stewart, 2014). It found that most papers were from protected areas in developed countries and by a handful of authors with few studies located outside protected areas, in developing countries, in threatened communities and/or biodiversity hotspots (Chapter 2). Most papers examined formal trail impacts using quantitative observational methods to measure compositional and some structural responses at the local scale (on trail and trail edges). The most common impacts included reduced vegetation cover, changes in plant species composition, trail widening, soil loss and soil compaction. Few papers assessed differences in impacts among different trail types, landscape-scale impacts, changes in impacts over time, species-specific responses and impacts on community functioning.

The literature review (Chapter 2) revealed that most trail impact research has been location-specific addressing what appear to be often management-focused problems in well-funded protected areas in only a handful of ecosystems. There needs to be a more holistic approach to this research that starts to summarise general trends in trail impacts. This approach requires the adoption of a more theory-driven, rather than crisis-driven, method gathering more thorough, ecosystem-scale data that will help guide appropriate trail design and enhance the sustainability of trail-based activities in natural areas. Specifically, more research is needed:

- 1) comparing the impacts of trails among different trail types, as well as among different ecosystems and biomes;

- 2) addressing impacts at a large scale, including over longer time frames and larger landscape-scales especially in areas where trails are a persistent and proliferate landscape feature;
- 3) addressing trail impacts on the structure and function of communities;
- 4) prioritising research on trail impacts in communities already threatened with extinction, including threatened plant communities and biodiversity hotspots.

The aims of the field results chapters (Chapters 3 - 7) addressed many of these gaps identified in the literature review (Chapter 2). An overall graphical summary of the results of the field research from each of the results chapters is presented in Figure 8.1.

Recreational trails: what are their impacts on threatened plant communities?

	Chapters 3 and 4	Chapter 5	Chapters 6 and 7
	Windswept Feldmark <i>Kosciuszko National Park</i>	Grey Box Grassy Woodland <i>Belair National Park</i>	Tall Open Blackbutt Forest <i>South-east Queensland</i>
Co m p o s i t	<div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> Herbs and shrubs </div>		
	<div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Grasses </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Herbs and shrubs </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Species richness </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Endemic species </div> <div style="border: 1px solid black; padding: 2px;"> Vegetation cover </div>	<div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Herbs, shrubs, bulbs </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Exotic grasses </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Species richness </div> <div style="border: 1px solid black; padding: 2px;"> Vegetation cover </div>	
St r u c t			<div style="border: 1px solid black; padding: 2px;"> Canopy cover </div>
			<div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Canopy cover </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Tree density </div> <div style="border: 1px solid black; padding: 2px;"> Sapling abundance </div>
		<div style="border: 1px solid black; padding: 2px; text-align: center;"> Remnant loss </div>	<div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Remnant loss </div> <div style="border: 1px solid black; padding: 2px;"> Fragmentation </div>
Fu n c t i o	<div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Facilitative habitat </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 2px;"> Succession </div> <div style="border: 1px solid black; padding: 2px;"> Functional composition </div>		

Figure 8.1 Summary of the key results of field research chapters assessing trail impacts in three threatened plant communities. Ruler/clock symbols represent spatial/temporal studies, respectively, while single squares represent direct local scale impacts, double squares are indirect local scale impacts and multiple squares are cumulative landscape scale impacts on compositional, structural and functional biodiversity. Dashes signify no impact and multi-head arrows, multi impacts.

8.3 Do recreational trails have impacts on threatened plant communities?

In the systematic quantitative literature review (Chapter 2), research assessing the impacts of trails on threatened species and plant communities was scarce with only eight published papers on the topic. The thesis focused on assessing trail impacts using three threatened plant communities differing in composition, structure and function and types of recreational trails present within them. These field research chapters (Chapters 3 - 7) demonstrated that recreational trails have a range of impacts on threatened plant communities.

The field research assessed a range of impacts and at different scales. At the direct local (on-trail) and indirect local (edge of trail) scales, impacts on plants included reduction in vegetation cover due to trails (Windswept Feldmark and Grey Box grassy woodland), changes in species richness (increasing in Windswept Feldmark, decreasing in Grey Box grassy woodland), changes in species and functional composition (Windswept Feldmark and Grey Box grassy woodland) and changes in the dominance of individual species (Windswept Feldmark and Grey Box grassy woodland). Some of these compositional changes intensified over time (Windswept Feldmark). Structural impacts included a loss of canopy cover, reductions in tree density and increases in sapling abundance (Tall Open Blackbutt forest). Functional impacts included a reduction in the amount, but not the quality of facilitation provided by a keystone species and also changes to succession (Windswept Feldmark). At the landscape scale, impacts of trails included overall loss of forest and fragmentation of once-contiguous remnants (Tall Open Blackbutt forest).

As with use-related impacts such as trampling (Hill and Pickering, 2009; Bernhardt-Römermann et al., 2011), the impacts of the trails themselves varied among the different plant communities and climates. In the alpine Windswept Feldmark (Chapters 3 and 4), the unsurfaced single trail resulted in compositional and functional impacts that persisted with changes in composition towards a graminoid-dominated community, reduced cover of the dominant keystone shrub and the subsequent reduction in habitat it provided for other species (Chapters 3 and 4). In alpine regions, recreational trails are particularly problematic, as specialised plant communities with limited distributions often occur in areas where visitation is concentrated (e.g. mountain tops and ridges) (Ballantyne and Pickering, 2012) and alpine plants often take a long time to recover from damage due to their slow growth-rates (Bayfield, 1979; McDougall and Wright, 2004; Pickering, 2010; Barros et al., 2014). The composition and structure of many alpine plant communities is governed by finely-balanced functional processes such as facilitation (Körner, 2003; Schöb et al., 2012) and so impacts on keystone species are particularly concerning. In addition, these communities are also threatened

by larger scale processes such as climate change. Active management decisions such as minimising trail impacts are an important, and manageable step towards increasing the resilience of these communities to more diffuse threats (Barros et al., 2014; Ballantyne and Pickering, 2015a).

In the urban Mediterranean-climate woodland (Chapter 5) and subtropical forest (Chapters 6 and 7) communities assessed there were networks of often informal unsurfaced trails rather than single trails. The proliferation of trails in these sites appears to be partly the result of multiple entry points to these remnants and their proximity to densely-populated urban areas (Chapter 7). Urban remnants of plant communities such as these are at particular risk from trail impacts, as trails are often easy to create, use is generally unregulated, proliferation is extensive and trail design is unsustainable due to frequent informal trails (Stenhouse, 2004; Ballantyne et al., 2014a). There was a diversity of trail types found in these remnants (> 9), ranging from small (< 1m wide) bare earth trails to large (5-7m wide) tarmac trails. The impacts of these trails were extensive, sometimes persisting more than 10m from the trails (Chapter 6) and cumulatively affecting between 4% and 20% of the total area of the communities assessed (Chapters 5 and 7). Because these communities are biodiverse and complex, there are strong compositional and structural effects from the trails including changes in the composition of vegetation on the trail edge (Chapter 5), reduced species richness (Chapter 5), changes in the abundance of disturbance-sensitive species (Chapter 5) and changes in tree density, canopy cover and sapling abundance (Chapter 6) leading to a proliferation of secondary-successional edges especially along larger hardened formal trails. The following sections discuss these results in more detail and explain how each of the threatened plant communities was affected by recreational trails. The discussion focuses on vegetation and soil impacts, including across different spatial scales, types of impacts and among different types of trails.

8.4 Do trail impacts occur at direct local, indirect local and cumulative landscape scales?

This thesis demonstrates that the impacts of recreational trails occur at direct local (on-trail), indirect local (edge effects) and cumulative landscape scales as proposed by Brooks and Lair (2005). Prior research had focused largely on the impacts of trails at direct (on trail) and indirect local (adjacent to trails) scales, looking at compositional and sometimes structural responses (Chapter 2). This thesis adds to the previous research by examining local scale impacts and extending to landscape scale impacts by assessing factors such as habitat loss and fragmentation.

Impacts at the direct local scale include little to no vegetation along the trail surface (Chapter 3), soil compaction (Chapters 5 and 6), soil erosion (Chapters 5 and 6) and canopy opening (Chapters 6 and

7). Some of these are common trail impacts, but they have rarely been demonstrated in threatened plant communities. Factors such as soil compaction and erosion varied depending on the type of trail, slope and soil type. For example, unhardened trails which lack 'proper' surfacing to cope with intense recreational use often became very widened (> 7m) especially on slopes (Chapters 6 and 7), resulting in massive soil erosion of up to 8,800,000m³ per remnant (Chapters 5 and 6) and average soil compaction over 4.5 kg ^{-cm²} (Chapters 5 and 6). The use of these trails clearly degrades on-trail conditions while precipitation exacerbates the damage causing gulying through surface runoff (Sun and Liddle, 1993; Cole, 2004; Ramos-Scharrón and MacDonald, 2007; Olive and Marion, 2009). This leads to avoidance behaviour among users which can then result in a positive feedback loop of trail widening and ultimately degradation of the trail environment (Wilshire et al., 1978; Olive and Marion, 2009; Wimpey and Marion, 2010; Marion and Leung, 2011) posing a safety hazard for future use (Pickering et al., 2010).

As deterioration of the trail occurs, other direct local scale impacts take place including to vegetation. This thesis showed that vegetation loss increases linearly with the width of the trail and cumulatively with the lineal extent of each trail type. Per unit area, wider trails caused extensive loss of vegetation. This was due to the large canopy gaps created in trail construction and maintenance, but also from trail widening due to intense or poorly-managed use. These wide trails tended however to be spatially scarce and so their cumulative impacts were low in the communities sampled. Narrow informal bare earth trails tended to be among the most abundant trails spatially and so their impacts on vegetation loss were greater (see below) but per unit area of trail, vegetation loss was low as they were narrow. Managing trail widening is therefore as important for threatened plant communities as it is for maintaining trail sustainability and surface conditions, as overly wide corridors can create large canopy openings with altered abiotic conditions that can select against important sensitive species (Bright, 1986; Pohlman et al., 2007; Hamberg et al., 2008; Atik et al., 2009; Wimpey and Marion, 2010).

Indirect local impacts (edge effects) included changes in plant species richness, species cover, tree structure, composition and function on the edge of the trail (Chapters 3, 5 and 6). In some situations impacts were very localised, with damage limited to < 1 m from the trail edge (Chapter 3), while in other situations trail impacts extended further into the community sometimes > 10 m from the trail edge (Chapter 5). For the more structurally-complex communities such as the Mediterranean woodland and subtropical forest, canopy cover, ground vegetation cover, shrub and bulb cover, species richness and tree density all declined on the edge of trails compared to vegetation further away, while weed cover, grasses and sapling abundance increased (Chapters 4, 5 and 6). These types

of impacts have been found for trails in other plant communities where trail construction and maintenance disturbs communities, opening of the trail corridor results in changes in abiotic conditions and visitor use exacerbates the disturbance ultimately leading to structurally-simple edge vegetation consisting of disturbance-tolerant plant species (Potito and Beatty, 2005; Delgado et al., 2007; Hamberg et al., 2008; Atik et al., 2009). These changes ultimately contribute towards a localised state of secondary-succession that has less habitat value for disturbance-sensitive fauna (Ballantyne and Pickering, 2015b). These impacts are likely to be even more important in closed communities such as rainforests where pre-disturbance conditions are very different to those created along trails (Harper and MacDonald, 2002; Harper et al., 2005; Pohlman et al., 2007).

In the alpine plant community with lower plant diversity and simpler vegetation structure, there was increased species richness and cover of some species along the edge of trails, including some endemics and species of conservation concern (Chapter 3). This may be because some species benefitted from the intermediate disturbance caused by trampling along the edge of the trail reducing the cover of the dominant shrub allowing these stress-tolerant species to increase, as found in other studies (Hall and Kuss, 1989; Roovers et al., 2004). Intermediate disturbance along the edge of trails through structurally-simple communities can reduce the cover of disturbance-sensitive dominant species like sclerophyllous shrubs and promote locally increased diversity among herbs and graminoids (Kutiel et al., 1999; Potito and Beatty, 2005; Lucas-Borja et al., 2011). However, the added barrier effect of the trail in Windswept Feldmark community had important consequences for the persistence of the dominant shrub further from the trail, affecting succession and facilitation and therefore the composition of those suites of species reliant on the shrub for establishment and protection.

Landscape-scale impacts from trails were found in the Grey Box grassy woodland and Tall Open Blackbutt forest (Chapters 5, 6 and 7) including from informally-created, complex, narrow trail networks often used by mountain bikers and hikers. These networks proliferated especially in unprotected, urban remnants of Tall Open Blackbutt forest often exceeding 660m^{-ha}, resulting in extensive loss of vegetation (sometimes up to 16%) and fragmentation exceeding that due to local urban development over a similar timeframe. This fragmentation, when compared with the few other studies using similar techniques, was found to be similar or greater than that caused by trails in some of the most popular protected areas in the USA (Moskal and Halabisky, 2010; Leung et al., 2011; Ballantyne et al., 2014a). The result can sometimes be that urban remnants contain a multitude of disturbed areas cumulatively exceeding that of the undisturbed core (Pickering et al., 2012; Ballantyne et al., 2014a). Urban, informal trails are a common source of internal

fragmentation because the highly disturbing activities they facilitate are becoming increasingly popular resulting in more trail creation (Stenhouse, 2004; Pickering et al., 2012; Ballantyne et al., 2014a). Furthermore, the trails themselves are relatively easy to create and maintain with hand tools and their development is often unregulated, especially in unprotected remnants (Pickering et al., 2010). The trails can also then act as conduits for the movement of exotic species, feral animals and pathogens into these plant communities (Benninger-Truax et al., 1992; Pickering et al., 2012). The resulting fragmentation of the once-contiguous natural areas into disjunct patches surrounded by corridors of disturbance is of concern, especially for threatened plant communities containing disturbance-sensitive species (Chapter 7; Ballantyne et al., 2014a).

Although this thesis has provided additional insight into landscape scale impacts of recreational trails, more research is needed. This includes understanding the sociological drivers behind trail-based fragmentation especially by informal trail creation and use (Walden-Schreiner and Leung, 2013), the effects of these trails on disturbance-sensitive species (e.g. epiphytes along trails, large mammals etc.), how best to monitor informal trails over time and how to assess the success of adaptive management strategies such as closure or rehabilitation of these trails.

8.5 Do trail impacts affect the structure, composition and function of threatened plant communities?

The biodiversity of the world's ecosystems exists in three facets: composition, structure and function (Noss, 1990). These facets are very much interrelated and for conservation measures to adequately understand and mitigate negative impacts on biodiversity, all three facets must be addressed (Noss, 1990; Noss, 1999). The majority of the papers assessing trail impacts on vegetation assess compositional responses (Chapter 2). In contrast there has been limited research addressing the structural impacts of recreational trails on vegetation and almost no studies addressing functional impacts (Chapter 2). Structural impacts include changes in the spatial and age structure of plants, habitat loss, litter depth and soil structure while functional impacts include changes in plant community processes such as seed dispersal, pollination, plant-soil feedback loops, succession, competition and facilitation. The results of the field research in this thesis demonstrated that recreational trails affect plant community structure and function, and corroborated previous research assessing compositional impacts of recreational trails.

The effects of recreational trails on the structure of Tall Open Blackbutt forest were assessed (Chapter 6 and 7). Wider, hardened trail types resulted in changes to the spatial and age structure of trees with reduced canopy cover and tree density and increases in sapling abundance on the edge of

these trails (Chapter 6). Such structural impacts may be due to the initial construction of the hardened trails due to the extensive and destructive processes involved. Large trees close to the edge of the trail are often selectively removed or damaged during construction reducing tree density along the trail edge (Buckley, 2004; Ledoux, 2004; Marion and Leung, 2004). The opening up of a linear exposed corridor, especially in forests, alters local abiotic conditions with increases in light penetration, wind-blow, air temperature and decreases in soil and atmospheric moisture occurring along the trail area (Delgado et al., 2007; Goosem, 2007; Pohlman et al., 2007; Laurance et al., 2009). These changes can promote the growth of more disturbance-tolerant secondary-successional species (including propagation and regeneration); plants such as ruderal weeds, vines and wind-dispersing species including members of the Asteraceae along the trail edge (Harper and MacDonald, 2002). Thus, direct disturbance to vegetation structure can lead to indirect changes in vegetation composition and where trails exist as extensive networks these structural-compositional impacts can become a landscape-level problem.

In open forests like Tall Open Blackbutt forest, the more likely effects of trail creation involve wind turbulence along the trail corridors rather than changes in light and temperature regimes. Such changes can promote the dominance of ruderal species and regrowth over larger, slow-growing woody species (Harper et al., 2005; Laurance et al., 2009). The width per unit area of the trail corridor has a major effect on wind gusts with wider gaps exposing mature trees to greater disturbance including unstable, but important old-growth habitat trees (Chapter 6). In more closed communities with relatively moist, shady, ambient conditions (e.g. rainforest ecosystems), trails could pose even more severe localised changes to vegetation structure due to the stark contrast in conditions before and after trail creation (Laurance et al., 2009). More work is needed in assessing the structural impacts of recreational trails on different plant communities with varying structures, especially in closed and/or structurally complex ecosystems.

To address functional impacts the barrier effect of a trail, inhibiting facilitation provided by a dominant shrub (*Epacris gunnii*) in the Windswept Feldmark community was observed (Chapters 3 and 4). The dominant, prostrate, slow-growing sclerophyllous shrub *E. gunnii* is an important keystone species providing protective microhabitats that facilitate the establishment of at least 44% of plant species in the community, including an endemic herb (Ballantyne and Pickering, 2015c). The hiking trail affects this facilitation process by reducing the abundance of *E. gunnii* shrubs on the leeward side of the trail. This reduction alters the wind profile across the leeward side of the ridge disrupting the regular pattern of succession and reducing the abundance of shrubs $\geq 5\text{m}$ from the trail (Chapter 4). The end result appears to be an overall reduction in the availability of facilitative

habitat on the leeward side of the trail and an increase in the amount of bare ground. Over time *E. gunnii* cover has continued to decrease thus reducing the net area of facilitative habitat available to the community (Chapters 3 and 4).

Trails are essentially linear, continuous and mostly bare corridors of disturbance that, used regularly, can create significant barriers to important small-scale ecological processes (Pickering et al., 2012). This can include important plant processes such as facilitation and succession. Although the study did not explicitly demonstrate trail barrier effects on succession, the loss of shrubs on the leeward side of the trail in the Windswept Feldmark is likely to have resulted from disturbance to the regular wind-profiling that, when uninterrupted, causes the uniform distribution of *E. gunnii* (Barrow et al., 1968; Costin et al., 2000). Overall composition will likely continue to change on the leeward side of the recreational trail as *E. gunnii* decreases and more stress-tolerant species such as graminoids and cushions colonise the bare ground (Chapter 4). In this light, the barrier effect of the trail on community functioning has an indirect link to changes in community composition. In slow-growing alpine plant communities, impacts on vegetation can take considerable time to reverse without extensive rehabilitation. A certain amount of predictive management is therefore needed for trail design in similar alpine ecosystems to reduce the chance of similar functional impacts occurring from the outset. This can include the use of raised trail infrastructure such as metal walkways that elevate the trail, remove the barrier effect and allow for contiguous vegetation underneath (Chapter 4).

There are many other ways in which trails could act as a barrier to other important community processes including inhibiting the spread of reproductive material (pollen and seeds) either side of a trail, particularly where propagules are transported by terrestrial organisms such as small mammals and ants, e.g. *Microtis* and *Leporella* orchid species (Peakall and Beattie, 1991). Trails may also inhibit plant-soil feedback processes such as nitrogen-fixation where local soil conditions become unfavourable for symbiotic microorganisms, e.g. extremes in soil temperatures denaturing enzymes (Waldrop and Firestone, 2006). Functional impacts such as these should be assessed to avoid long-term and possibly irreversible impacts on plant communities used for trail-based recreation.

In addition to the lesser known structural and functional impacts of recreational trails on plant communities, the study also documented compositional impacts in the Windswept Feldmark (Chapter 3) and Grey Box grassy woodland (Chapter 5) communities. Composition was affected at the indirect local scale including reduced vegetation cover and a decline in shrub and bulb species, but an increase in graminoids, and in the Windswept Feldmark, increases in some herb species. Species richness also declined along some trails in the Grey Box grassy woodland community, but increased in the Windswept Feldmark.

Compositional changes along trails can be a result of changes in structure and function caused by the creation and use of trails (Ballantyne et al., 2014b). The creation of trails often disturbs local vegetation structure and soils through digging, grading and extraction thus promoting more stress-tolerant and competitive species (Buckley, 2004; Ledoux, 2004; Ballantyne and Treby, 2015). The use and maintenance of trails can then sustain the disturbed ecosystem structure selecting for more disturbance-tolerant species resulting in a plant composition of tough rhizomatous grasses and sedges, rosette and mat-forming perennials and fast-growing weeds (Liddle, 1997). Sclerophyllous and woody species are broken easily, recover slowly and therefore decline along trails (Hill and Pickering, 2009; Bernhardt-Römermann et al., 2011). Some of these more structural plants are keystone species or 'ecosystem engineers' and so their loss can have knock-on effects for community functioning (Ballantyne and Pickering, 2015a). In some cases however, fast-growing woody weed species increase along trails where their seed are preferentially transported along trail corridors by visitors and animals (Nemec et al., 2011).

As a result of the novel disturbed environment along many trails, total species richness can increase as more species are able to colonise trail edges (Potito and Beatty, 2005; Lucas-Borja et al., 2011). This can include native ruderal species and exotic weeds but occasionally species of conservation concern that benefit from intermediate disturbance (Benninger-Truax et al., 1992; McDougall and Wright, 2004; Baret and Strasberg, 2005; Potito and Beatty, 2005). In the Grey Box grassy woodland, for example, overall species richness declined, but weed grass richness increased along the trails (Chapter 6) while in the Windswept Feldmark, overall richness increased along the trail edges consisting of a diverse composition of natives (Chapter 3). The exact changes in species richness caused by trails are strongly dependent on the type of community and the tolerance of its constituent species. Those regularly exposed to natural disturbance regimes could benefit from intermediate disturbance while those in stable environments like rainforest systems will likely experience marked changes in composition (Harper and MacDonald, 2002; Bernhardt-Römermann et al., 2011). The use of the trail also contributes to compositional change over time acting as a conduit for many invasive propagules brought in by visitors and animals (Benninger-Truax et al., 1992; Ansong and Pickering, 2013; Ansong and Pickering, 2014).

While the types of impacts are important and intrinsically-related among the three facets of biodiversity, the severity of trail impacts on plant communities often differs among types of trails. The next section looks at this issue in more detail.

8.6 Do impacts differ in type and severity among different types of recreational trail?

Prior to this thesis, there were only a handful of papers that specifically compared vegetation impacts among different types of trails (Godefroid and Koedam, 2004; Hill and Pickering, 2006; Müllerová et al., 2011). I found clear differences among some types of trails in the severity and types of direct and indirect impacts, and in their landscape-scale impacts (Chapters 4, 5, 6 and 7). Direct local impacts included differences in on-trail condition with some trails characterised by extensive soil erosion and soil compaction, while indirect local impacts included changes in vegetation along trail edges. Landscape scale impacts also differed with some types of trails resulting in overall greater loss of vegetation and fragmentation than others. Differences were found between formal and informal trails, among trails of differing width, among trails with different surfaces and among trails with different spatial extents. An outline of the nature of these differences is presented in Table 8.1.

On-trail conditions were better for formal and hardened trails such as management-designated gravel and tarmac trails. Once built, these trails experienced limited soil erosion and compaction compared to unhardened trails. These results are consistent with other studies addressing trail degradation that found that resource hardening reduces on-trail degradation (Wimpey and Marion, 2010). Some hardened trail types however were better than others. Loose-edged trails built with substrates such as gravel and dolomite chips underwent moderate erosion because the substrate is not fixed and can wash away with precipitation and flooding (pers. obs.) which can then damage adjacent vegetation, reduce water quality and add nutrients to nearby systems (Ramos-Scharrón and MacDonald, 2007; Müllerová et al., 2011). In fact, the on-trail condition of many gravel trails was actually poorer than for some of the narrower types of unsurfaced, informal trails (Chapter 5). Overall, hard-edged trails such as tarmac were among the most effective at maintaining on-trail conditions, and could be expanded to include “soft” tarmac, concrete, raised walkways and pavers (Hill and Pickering, 2006).

As discussed previously, informal, bare earth trails experienced the poorest on-trail conditions overall including great variance in width (0.9 – 4.8m), high erosion (sometimes > 6,000,000m³) and compaction (> 4.3 kg^{-cm²}) (Chapter 5). However, where maintained to a narrow tread (< 1m) these trails had relatively good conditions with occasionally less soil loss than gravel trails (Chapter 6). Keeping these trails narrow over time and managing increasing degradation by use and weather is a challenge for natural area managers. This is often why many choose to harden trails in favour of long-term sustainability (Manning et al., 2006; Tomczyk, 2011; Wimpey and Marion, 2011).

Sociological research on the process by which unsurfaced trails degrade over time and with varying usage, could begin to unravel the success of different trail surfaces and allow managers to design trail networks more appropriately (Walden-Schreiner and Leung, 2013).

A different pattern was found for impacts to vegetation along trail edges (indirect local impacts) compared to on-trail impacts (Chapters 5 and 6). Formal, hardened trails tended to cause greater damage and changes to vegetation per unit area than unhardened trails. This included altered composition and structure (dominated by weed grasses and regenerating species), reduced species richness, reduced canopy cover and more penetrative edge effects (Chapters 5 and 6). This suggests that great disturbance during construction and maintenance of hardened trails may result in greater and lasting damage to vegetation on the trail edges. Where unhardened trails essentially require just clearing and maintenance of a bare corridor, hardened trails often require extensive clearance zones, digging, levelling and grading, irrigation and channelling, fencing, surfacing and maintenance of a clear tread by slashing, spraying and burning (Buckley, 2004; Ledoux, 2004; Ballantyne and Treby, 2015). In some cases the total work zone for these trails can extend 20m either side of the trail causing considerable spatial degradation, much of which is difficult to rectify over the long-term without rehabilitation efforts (Buckley, 2004; Ledoux, 2004).

Unsurfaced, often informal, trails maintained more 'natural' vegetation along their edges with greater similarity to control composition, limited declines in herb or bulb species cover, few reductions in canopy cover and limited alteration to trail-side tree density (Chapters 5 and 6). The creation of these trails requires little disturbance to trail edges often just involving initial clearing and subsequent use. These trails often provide access for more passive forms of recreation such as hiking and bird-watching allowing people to move among natural areas causing little disturbance overall. However, where use of the trails becomes more intense however (e.g. mountain-biking or dirt-biking) trails can quickly degrade and widen causing similar vegetation loss and changes to plant community structure and composition approaching that caused by hardened trails (Chapters 5 and 6).

Where unsurfaced trails were wide (> 4m) the vegetation impacts were more severe including reduced cover and species richness of vegetation and some changes in composition, although less severe than hardened trails (Chapters 5 and 6). These impacts are likely due to the creation of large canopy gaps over overly-wide unsurfaced trails that lead to a bare and exposed corridor that has an altered abiotic environment compared to undisturbed vegetation (Pohlman et al., 2007; Olive and Marion, 2009; Wimpey and Marion, 2010). If intensive use continues along these trails, on-trail condition deteriorates (especially on slopes) leading to avoidance behaviour and further trail

widening (Leung and Marion, 1996). Wider trails generally create a more exposed abiotic environment, factors which can benefit some species such as Mediterranean grasses and stress-tolerant herbs, but often exclude more sensitive species (Lucas-Borja et al., 2011).

At the landscape scale, trail types differed again in their impacts (Chapter 7). While per unit area, wider and hardened trails caused great vegetation loss and changes in structure and composition, cumulatively, it was narrow, informal bare earth trails that caused the greatest overall vegetation loss and fragmentation. These trails become dense and result in more extensive vegetation loss along their treads, with greatest loss where they proliferate in small urban remnants (Ballantyne et al., 2014a). Some small urban remnants of Tall Open Blackbutt forest for example were predicted to contain less than 50% of the original forest area in an undisturbed state and lost up to 20% of forest along the trails themselves. The management of informal trails is becoming of increasing concern for urban landscapers and protected area managers worldwide with researchers beginning to unravel not only the environmental effects, but also the sociological drivers and patterns associated with their creation (Leung et al., 2011; Walden-Schreiner and Leung, 2013; Ballantyne et al., 2014a; Yang et al., 2014). Despite the spatial proliferation of these types of trails, they have less impact per unit area on edge vegetation than wider or hardened trails.

Table 8.1 Summary of the impacts of different types of recreational trails among the three threatened plant communities in Australia. A downward arrow signifies a decline in the dependent variable caused by each trail type, while an upward arrow signifies an increase in the dependent variable with the size of the arrow (large, medium or small) indicating the intensity of the impact. A dash signifies no impact.

Dependent Variable	Trail Type								
	Small bare earth	Medium bare earth	Large bare earth	Medium grass	Medium gravel	Large gravel	Medium Tarmac	Large Tarmac	Medium concrete
Vegetation cover	↓	↓	↓		↓			↓	
Species richness	↓	↓	↓		↓			↓	
Cover of shrubs	—	—	—		—			↓	
Cover of herbs/bulbs	—	↓	↓		↓			↓	
Cover of graminoids	—	—	—		↑			↑	
Canopy cover	—	↓	↓	↓	↓	↓	—		—
Tree density	↓	↓	↓	↑	↓	↓	↓		↓
Sapling abundance	—	↑	↑	↑	↑	↑	↑		↑
Habitat loss	↑	↑	↑	↑	↑	↑	↑	↑	↑
Fragmentation	↑	↑	↑	↑	↑	↑	↑	↑	↑
Facilitation		↓							

8.7 Research contribution to knowledge

This thesis makes an original and innovative contribution to research on recreational trail impacts including in threatened plant communities. It analyses the current state of research into trail infrastructure impacts and highlights how impacts occur at a range of spatial scales, affect all facets of biodiversity and that the type and intensity of impacts vary among different types of trails (Figure 8.1).

Particular contributions to knowledge include demonstrating how trails affect plant communities at a landscape scale by causing significant habitat loss and fragmentation. The indirect local scale edge effects (e.g. reduced tree density or changing composition) then accumulate thus causing landscape-scale impacts across whole remnants or plant communities.

Another important contribution was to demonstrate that trails, like roads and other forms of linear infrastructure, act as barriers inhibiting important functional processes in plant communities such as facilitation. This suggests that some commonly-observed changes to vegetation along trails such as altered composition may be secondary effects of alterations to underlying functional processes. As such, these effects may be much longer-term than initially thought and rectifying these impacts may take considerable time and effort, especially in slow-growing communities such as in alpine areas.

Finally, I used multiple comparisons of different trail types to identify different types and severities of impacts. While on-trail conditions of unsurfaced, often informal trails are generally poor and cause use-related and sustainability concerns, the vegetation along their edges can be in good condition. Hardened trails, on the other hand, can have better on-trail conditions due to resource hardening, but may have altered vegetation along their edges. Cumulatively however, the impacts of the different trails depend on the total length of the trail among other factors. These sorts of comparative studies can help gazette what trails cause what types of impacts therefore providing important data for sustainable trail development and management.

8.8 Implications for the management of recreational trails

8.8.1 General implications for the management of recreational trails in threatened plant communities

The results of this thesis provide somewhat of a 'Catch 22' situation for those managing recreational trails in threatened plant communities, as well as more generally. Concentrating on maintaining on-trail conditions for sustainability and visitor safety can still result in changes to edge vegetation due to trail construction and maintenance. Alternatively, bare trails composed of earth can quickly degrade leading to on-trail degradation and safety hazards, can cause persistent functional impacts and they can also proliferate extensively in popular sites causing habitat loss and fragmentation.

Managers need to adopt a holistic approach to sustainable trail development. This involves (1) visitor surveys to determine types of use occurring including when and where, the acceptability of different types of use and the design of trails that meet the requirements of 'acceptable' usage, (2) a survey of key sensitive areas and ecosystem functions that should remain undisturbed, (3) the designation of high use areas in which trail systems should be hardened to limit direct local impacts but follow up with vegetation rehabilitation to limit indirect local impacts and (4) the creation of unsurfaced trails in less intensely-used areas to reduce indirect local impacts, but restrict the network to a minimum viable spread to reduce habitat loss and fragmentation (Figure 8.2).

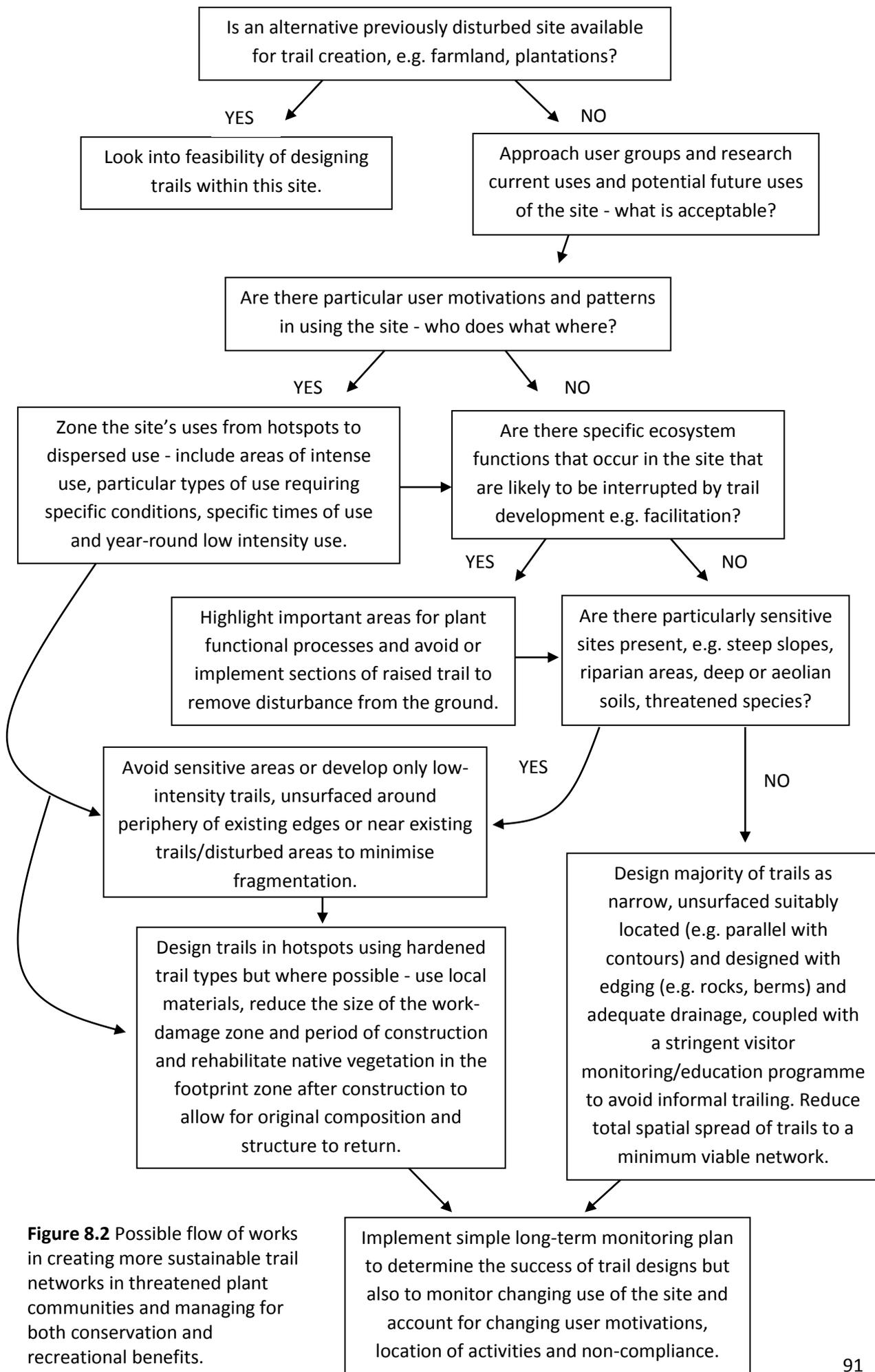
In threatened plant communities, there needs to be a decision prior to any construction of trails as to whether an alternative, non-conservation value area can be used for the purpose, e.g. farmland or plantation forest. If not, then limiting trail creation to nearby existing networks, or along peripheral existing edges will minimise internal disturbance to important core areas. The key points in design are (1) reducing the impacts of the trails at the landscape scale (informal trail management plan, minimum viable network design), (2) reducing impacts on important community processes (avoidance or for vegetation, raising the trail e.g. metal walkways), (3) reducing impacts on structure and composition, especially in complex and biodiverse communities and (4) applying a temporal monitoring scheme to determine the success and failures of the trail design over time as has been done in the Tasmanian highlands (Dixon and Hawes, 2015). While such a program of intense planning and monitoring requires funding, there are likely to be more sources of funding where the development takes place in well-known conservation-value ecosystems.

8.8.2 Specific management implications relating to the plant communities studied in this thesis

As a result of Chapters 3 and 4 and an additional paper published during my candidature (Ballantyne and Pickering, 2015c), I submitted a nomination to the New South Wales Scientific Committee to have the Windswept Feldmark plant community protected by law. After completing and submitting the nomination, an initial assessment by the committee, a period of public exhibition and a final determination by the New South Wales Environment Minister, the nomination is due to be finally accepted and published in September 2015. This plant community is now preliminarily listed as a critically endangered ecological community under the New South Wales Government Threatened Species Conservation Regulation 2010 on the grounds of its considerable risk of extinction due to climate change, fire and recreational trail impacts (New South Wales Scientific Committee, 2015).

A technical report was submitted to the South Australian Department of Environment, Water and Natural Resources in April 2015 outlining the impacts of different types of recreational trails to the composition of Grey Box grassy woodland in Belair National Park, Sturt Gorge Recreation Park, Shepherd's Hill Recreation Park and Blackwood Hill Reserve (Ballantyne and Treby, 2015). This report presents the impacts of different trail types on surrounding vegetation and suggests appropriate management recommendations for future trail designs for the department and local city council. It also outlines the extent of fragmentation caused by informal trails in the area and suggests that these trails are removed or at least reduced.

Finally, forthcoming workshops with council, government and local public stakeholders to discuss the future management of recreational trails in Tall Open Blackbutt forests in south-east Queensland are being planned.



8.9 Future research directions

Some limitations need to be addressed in the interpretation of the results in this thesis. Although there were differences among trail types in the severity of their impacts on vegetation and soils, I did not assess how impacts of use varied. The use of these trails and the time since they were created likely have strong, confounding influences on some of the results found. For example, although I found smaller, unsurfaced trails had less impact on edge vegetation per unit area, where such trails become used for mechanised, intense recreational activities such as dirt-biking, the impacts will likely increase. This is an important factor to account for in future research, but often the data is difficult to reliably and systematically obtain. However, in this thesis, the fact that there was stratified random sampling of each trail type across segments of that trail in separate locations, removes some of the data 'noise' associated with such use-related impacts.

Another limitation was the inability to address specific temporal impacts relating to the construction and maintenance of trails. In Chapter 3 it was shown that trails contribute to temporal changes in community composition, but these changes can also arise from climatic changes over the same 10 year period. The use of experimental designs creating trails through plant communities with sufficient replicates is unlikely to be feasible, especially in threatened plant communities. Future research could however address trail impacts using already-disturbed or 'brownfield' sites.

Overall, there is a need for more research to better understand the impacts of recreational trails in threatened plant communities. Despite increasing knowledge of how the use of natural areas for nature-based tourism and recreation can degrade them, knowledge of the impacts of infrastructure provided for these activities is still comparatively poor. For example, more research is needed on how trails affect community processes such as seed and pollen dispersal, plant-soil feedback loops and facilitation, especially for threatened communities and threatened species. Research on temporal impacts is also required including monitoring the success of trail creation and closure over time. Comparing new and emerging trail surfaces such as raised walkways, Geoweb®, "soft" tarmac and pavers is also important to document the types and severity of impacts they have on vegetation and soils. Finally, like trail use-related impacts, trail infrastructure impacts differ among ecosystems and climates. There is a need for a greater biogeographical spread of research including in areas of high biodiversity currently experiencing rapid development of nature-based tourism and recreation.

8.10 Conclusions

In conclusion, recreational trails have significant impacts on the conservation of threatened plant communities. They are often among the few developments permitted in threatened plant communities and so their impacts are important to mitigate. Sensible management of the use of these communities for nature-based tourism and recreation through more strategic and sustainable trail design is a step in the right direction to reduce degradation. Using three separate threatened plant communities in Australia, I found that trails cause impacts at direct and indirect local as well as landscape scales, impact compositional, structural and functional facets of biodiversity and that these impacts differ considerably among different trail types. These results indicate that more foresight is required in the design and implementation of trail networks in threatened plant communities.

In Australia, as elsewhere in the world, natural areas are increasingly used for human development, while the surviving remnants are increasingly used for nature-based tourism and recreation as a means of justifying their conservation. The resulting increase in threatened plant communities means that important remnants containing rare biological assemblages, processes and ecosystem services are experiencing increasing disturbance. Although the promotion of natural areas, including threatened plant communities, is important to inspire future generations to appreciate and conserve them, this must be done in a sustainable way. This includes the creation and management of sustainable recreational trails which are a primary means of visitor access to these areas. More attention must be paid to the construction, maintenance and presence of trails as permanent features in these landscapes. Comparing how different types of trails affect different types of communities and ecosystems is also important, and can lead to the creation of regional sustainable trail design protocols. Adjusting trail design to reduce many of the impacts discussed in this thesis is a relatively achievable task using some of the recommendations presented. These more holistic and strategic plans will help minimise impacts that may otherwise degrade the very resource people come to visit. By alleviating these smaller-scale impacts such as from recreational trails, plant communities are also likely to have increased resilience to larger-scale impacts, thus assisting their survival into the future.

8.11 References

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Appendices

Appendix 1 Griffith University policy for the submission of PhD theses as a series of published and unpublished papers. Available <http://www.griffith.edu.au/higher-degrees-research/current-research-students/thesis/preparation/thesis-as-a-series-of-published-unpublished-papers>, accessed 17 June 2015.



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This information is not relevant to those students enrolled in the PhD by Publication program, 6002. PhD by Publication students should refer to the program specific thesis formatting information.

HDR Candidates may organise their thesis as a series of papers. This thesis format may include one or more papers that have been prepared, submitted, or accepted for publication. A Doctoral or MPhil thesis prepared in this way is not a different degree. There are several advantages to organising a thesis in this way:

- » Preparing papers for publication saves time when preparing the thesis for examination as papers may make up one, or several, chapters within the thesis.
- » It is to your advantage to publish work from your thesis as a means of disseminating your research, and developing your writing skills.
- » It may improve the quality of your thesis as part of your thesis has already been subjected to peer review.
- » Examiners may have more confidence in your thesis if they can see that you have already published your research. In addition, you will have already met one of the criteria of examination, with the thesis suitable for publication.

In addition, as a candidature requirement all doctoral candidates are expected to have at least one peer reviewed output accepted for **publication during candidature**. Whilst not compulsory, students are encouraged to include this publication in the body of the thesis due to the advantages as outlined above.

Conditions

Requirements for inclusion of papers

A thesis may include published or unpublished papers where such papers have been produced under supervision and during the period of candidature; and where the quality of such papers is appropriate to Doctoral, or MPhil, level research. For the purpose of this requirement, papers are defined as a journal article, conference publication, book or book chapter. Papers which have been rejected by a publisher must not be included unless they have been substantially rewritten to address the reviewers' comments, or have since been accepted for publication.

Overall, the material presented for examination needs to equate to that which would otherwise be presented in the traditional

Extent of student's contribution

The student should normally be principal author (that is, responsible for the intellectual content and the majority of writing of the text) of any work included in the body of the thesis. Where any work has been jointly authored, a signature from the corresponding author is required in order to include the material in the body of the thesis. Co-authored work in which the student was a minor author can only be used and referenced in the way common to any other research publication cited in the thesis.

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Students are required to advise the copyright status of each publication included in the thesis via a declaration to be inserted in the thesis, as detailed below.

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Format

General

Consult the [thesis preparation and formatting guidelines](#) for general information about the requirements for formatting the thesis.

Format of papers

A thesis may entirely or partly be composed of papers. Where a thesis is entirely composed of papers, there is no minimum requirement for the number of papers that must be included and is a matter of professional judgment for the supervisor and the student. The papers may be rewritten for the thesis (post-print or pre-print versions); or they can be inserted in their published format, subject to copyright approval as detailed above. A paper may form a single chapter, or several papers may form successive chapters. Passages from papers may be transferred directly or in modified form into one or more of the chapters of the thesis. Students may repaginate the papers to be consistent with the thesis. However, this is at the discretion of the student.

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The thesis must be more than a collection of papers in the following ways. The chapters must be in logical order and strongly linked together. Students who submit a thesis in this format may introduce each new chapter with a foreword which introduces the research and establishes its links to previous chapters. In general, the thesis should include a general introduction which sets out the context of the thesis. The thesis should also include a conclusion which draws together the main findings of the thesis and establishes the significance of the work.

Declarations

All theses that include papers must include [declarations](#) which specify the publication status of the paper(s), your contribution to the paper(s), and the copyright status of the paper(s). The declarations must be signed by the corresponding author (where applicable). If you are the sole author, this still needs to be specified. The declaration will need to be inserted at the beginning of the thesis, and for any co-authored papers, additional declarations will need to be inserted at the beginning of each relevant chapter. You may wish to consult the [declaration requirements for inclusion of papers](#) diagram to ensure that you insert the correct declaration(s) within the thesis. Please note that completion of the declaration(s) does not negate the need to comply with any other University requirement relating to co-authored works as outlined in the [Griffith University Code for the Responsible Conduct of Research](#).

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