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The impacts of vehicle disturbance on NSW saltmarsh: implications for rehabilitation

Shannon E. Schofield

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Abstract

Coastal saltmarshes are recognised globally as important ecological communities that are increasingly under threat. The use of off-road vehicles in saltmarsh environments has been identified as a very serious and rapidly escalating threat to these ecosystems. Despite this, vehicle disturbance within saltmarsh ecosystems has not been widely studied, particularly in the Australian context. Further understanding of the nature of this threat is required to provide knowledge for potential rehabilitation strategies.

This study aimed to assess the impacts of vehicles on saltmarsh, at two locations on the South Coast of NSW, Australia. I adopted a multi-disciplinary approach to assess the impacts of vehicles on a range of biotic and abiotic variables. Biotic variables included abundance and composition of both the standing vegetation and the soil seed bank. The soil seed bank was assessed via a seedling emergence study, whereby soil samples were placed in greenhouses under conditions favourable for germination, and counted and identified as they emerged. Abiotic variables assessed included physical soil properties, chemical soil properties, micro-topography and hydrology. Physical and chemical soil properties were examined using a combination of field and laboratory techniques. The spatial extent of vehicle damage was determined, as well as the impacts of vehicles on micro-topography and hydrology using Geographic Information Systems (GIS).

This study demonstrated that vehicles adversely impact saltmarsh ecosystems in a number of ways. Vegetation cover was on average 90% lower within vehicle tracks and the average number of plant species was halved. Changes to vegetation species composition were associated with vehicle damage, with impacted areas more likely to comprise species characteristic of the lower saltmarsh zone. The soil seed bank was adversely affected by vehicle disturbance, with an 80% reduction in average seed density within the soil of tracks. As the soil seed bank plays a vital role in vegetation recovery post-disturbance, reduced seed densities within the soil of vehicle tracks were considered major barriers to natural regeneration of damaged areas.

Vehicle damage was also associated with changes to the local abiotic environment. Increased soil compaction was identified as a major impact of vehicle disturbance. Overall soil quality was found to be reduced in areas of disturbance, with lower levels of soil organic matter within vehicle damaged areas. Vehicle tracks were also associated with localised depressions in the marsh surface and thus, altered hydrological conditions. These factors were considered to have significant influence on ecological function of the saltmarsh and were identified as major factors limiting regeneration in vehicle damaged areas. Investigation of the impacts of vehicles on South Coast saltmarsh sites revealed that unassisted regeneration may not always be possible, and more active rehabilitation measures may be required in response to vehicle disturbance.

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The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part or otherwise for any other degree or qualification.

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Cover Photo: Vehicle disturbance on saltmarsh vegetation, Bermagui River (2016)

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Abstract

Coastal saltmarshes are recognised globally as important ecological communities that are increasingly under threat. The use of off-road vehicles in saltmarsh environments has been identified as a very serious and rapidly escalating threat to these ecosystems. Despite this, vehicle disturbance within saltmarsh ecosystems has not been widely studied, particularly in the Australian context. Further understanding of the nature of this threat is required to provide knowledge for potential rehabilitation strategies.

This study aimed to assess the impacts of vehicles on saltmarsh, at two locations on the South Coast of NSW, Australia. I adopted a multi-disciplinary approach to assess the impacts of vehicles on a range of biotic and abiotic variables. Biotic variables included abundance and composition of both the standing vegetation and the soil seed bank. The soil seed bank was assessed via a seedling emergence study, whereby soil samples were placed in greenhouses under conditions favourable for germination, and counted and identified as they emerged. Abiotic variables assessed included physical soil properties, chemical soil properties, micro-topography and hydrology. Physical and chemical soil properties were examined using a combination of field and laboratory techniques. The spatial extent of vehicle damage was determined, as well as the impacts of vehicles on micro-topography and hydrology using Geographic Information Systems (GIS).

This study demonstrated that vehicles adversely impact saltmarsh ecosystems in a number of ways. Vegetation cover was on average 90% lower within vehicle tracks and the average number of plant species was halved. Changes to vegetation species composition were associated with vehicle damage, with impacted areas more likely to comprise species characteristic of the lower saltmarsh zone. The soil seed bank was adversely affected by vehicle disturbance, with an 80% reduction in average seed density within the soil of tracks. As the soil seed bank plays a vital role in vegetation recovery post-disturbance, reduced seed densities within the soil of vehicle tracks were considered major barriers to natural regeneration of damaged areas.

Vehicle damage was also associated with changes to the local abiotic environment. Increased soil compaction was identified as a major impact of vehicle disturbance. Overall soil quality was found to be reduced in areas of disturbance, with lower levels of soil organic matter within vehicle damaged areas. Vehicle tracks were also associated with localised depressions in the marsh surface and thus, altered hydrological conditions. These factors were considered to have significant influence on ecological function of the saltmarsh and were identified as major factors limiting regeneration in vehicle damaged areas. Investigation of the impacts of vehicles on South Coast saltmarsh sites revealed that unassisted regeneration may not always be possible, and more active rehabilitation measures may be required in response to vehicle disturbance.

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List of Abbreviations

4WD	Four-wheel drive
AHD	Australian Height Datum
ANOVA	Analysis of Variance
API	Aerial Photograph Interpretation
ASL	Above Sea Level
ATV	All-Terrain Vehicle
BD	Bulk density
DEM	Digital Elevation Model
EC	Electrical Conductivity
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999
ERC	Ecological Research Centre
FM Act	Fisheries Management Act 1994
GIS	Geographic Information System
HAT/LAT	Highest/Lowest Astronomical Tide
LGA	Local Government Area
LiDAR	Light Detection and Ranging
LOI	Loss on Ignition
LPI	Land and Property Information
MC	Moisture content
ORV	Off-road vehicle
PCA	Principle Components Analysis
PERMANOVA	Permutational Multivariate Analysis of Variance
RTK GPS	Real-time kinematic global positioning system
SE	Standard error
SE LLS	South East Local Land Services
SIMPER	Similarity Percentages
TSC Act	Threatened Species Conservation Act 1995

1 Introduction

1.1 Study Context

Coastal saltmarshes border saline water bodies and can be described as intertidal communities, dominated by herbs, grasses and low shrubs (Adam 1990; Adam 2009). They occur on soft substrate environments protected from the full force of surf, on the shores of estuaries, embayments and low wave energy coasts (Adam 1990; Laegdsgaard 2006).

Saltmarshes are recognised globally as ecosystems of high ecological value, and have a number of important functions (Adam 2009). Hydraulically, they protect the coastal zone by damping waves, storing surge waters and stabilising fine sediment (Laegdsgaard 2006; Allen 2009). Other ecosystem services provided by saltmarsh include highly efficient carbon sequestration (Mcleod et al. 2011; Howard et al. 2014a) and trapping of contaminated runoff from rural and urbanised areas (Chenhall et al. 1992). Ecologically, saltmarsh provides vital habitat for a diverse range of fauna, including invertebrate, fish, bird and mammalian species (Laegdsgaard 2006; Connolly 2009; Spencer et al. 2009).

For centuries, coastal saltmarshes throughout the world have experienced severe degradation as a result of human activity (Adam 2002). Many saltmarshes have been ‘reclaimed’ for agricultural, industrial and residential purposes (Adam 2002; Laegdsgaard et al. 2009). In particular, the NSW coastline of Australia has experienced large-scale losses, with an estimated 60% of coastal wetlands (including saltmarsh) lost or degraded over the past 200 years (Bowen et al. 1995). Although their significance has been widely realised in more recent years, numerous activities detrimental to saltmarsh continue to occur (Adam 2002).

The use of off-road vehicles in saltmarsh environments can cause localised and widespread damage, and is considered a very serious and rapidly escalating threat to saltmarsh ecosystems (Kelleway 2005; Laegdsgaard et al. 2009; Trave & Sheaves 2014). The decrease of saltmarsh areas in many parts of Australia has been directly attributed to off-road vehicle use (Laegdsgaard et al. 2009), but the total spatial extent of damage is not known. The most apparent impact of vehicle disturbance to saltmarsh is severe denudation of vegetation, which can result in large patches of bare ground (Figure 1) (Kelleway 2005). Other impacts include changes to the soil environment, such as increased soil compaction (Blionis & Woodin 1999; Kelleway 2005; Trave & Sheaves 2014). Vehicle disturbance has also been shown to have negative impacts on saltmarsh fauna, including adverse impacts on crab communities (Kelleway 2005; Trave & Sheaves 2014).

Figure 1: Vehicle damage to Sarcocornia quinqueflora saltmarsh community at McLeod's Creek, Batemans Bay

1.2 Project scope

South East Local Land Services (LLS) intends to support a range rehabilitation projects on coastal wetlands on the NSW South Coast, including saltmarsh in priority areas. Vehicle disturbance has been identified as a key threat to saltmarsh on the South Coast and is a major management concern for LLS. The organisation wanted to explore the potential for unassisted regeneration of saltmarsh impacted by vehicles. In particular, LLS wanted to know if damaged areas were likely to recover without assistance after removal of vehicle access, or if more active rehabilitation measures would be required.

1.2.1 Study objectives

The overall objective of this study was to examine the impacts of vehicle disturbance to NSW saltmarsh environments. This objective was considered important as it would provide insight into potential rehabilitation strategies. A multidisciplinary approach was applied to address this aim, by combining aspects of plant ecology, soil science and spatial science. The overall objective of this study was separated into two key aims;

1. To assess the impacts of vehicle disturbance on NSW South Coast saltmarsh using biotic and abiotic variables
2. To assess the capacity for passive (unassisted) rehabilitation in vehicle damaged saltmarsh areas.

1.2.2 *Key questions and hypotheses*

The overarching research question for this thesis was;

What are the specific impacts of vehicle disturbance to saltmarsh environments?

This question was separated into biotic and abiotic components, as outlined in figure 2.

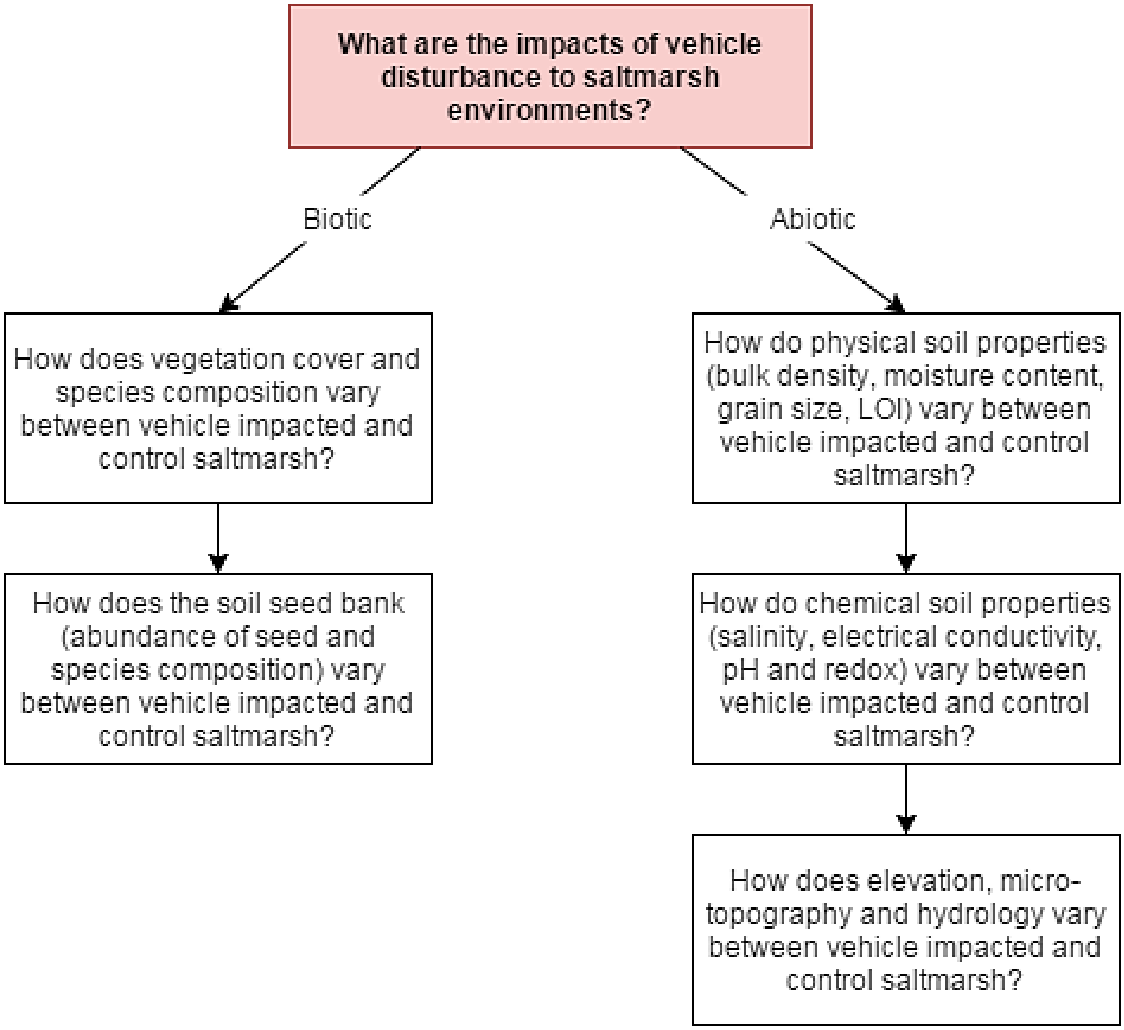

Figure 2: Key research questions separated into biotic and abiotic components

One of the most evident impacts of off-road vehicles to saltmarsh is reduced vegetation cover (Wisheu & Keddy 1991; Kelleway 2005). This impact has been visibly observed at both locations included in this study. I hypothesised that vegetation cover would be significantly reduced in vehicle impacted areas. I also anticipated that vegetation composition would vary significantly between vehicle-impacted and adjacent control saltmarsh, due to changes in localised environmental conditions from vehicle impacts.

I hypothesised that the soil seed bank, specifically abundance of seed and species composition, would not be significantly impacted by vehicle disturbance. This hypothesis was formulated with the knowledge that vehicle tracks are in close proximity to unaffected vegetation and therefore, are close to sources of seed. Although there may be some reductions in seed density due to low vegetation cover, saltmarsh seeds are generally dispersed tidally (Adam 1990; Bakker et al. 1996), and therefore dispersal into vehicle tracks should not be significantly impaired.

Physical soil properties were expected to be influenced by vehicle disturbance. I hypothesised that vehicle disturbance would be associated with an increase in soil bulk density and penetration resistance, due to compaction processes from vehicle passage. I also anticipated that vehicle disturbance would be associated with decreased Loss on Ignition (LOI), due to lower soil organic matter from reduced vegetation abundance. Similarly, I hypothesised that soil grain size would be higher in impacted saltmarsh due to reduced organic content. I anticipated that the effects of vehicle damage on soil properties would be greater at the surface of the soil than the sub-surface.

I hypothesised that chemical soil properties including salinity and electrical conductivity would be influenced by vehicle disturbance. Salinity and electrical conductivity were expected to be higher in areas of vehicle damage where vegetation had been removed, because there is less vegetation shading the ground. This is likely to cause higher rates of evaporation and retention of ions. Redox potentials indicate waterlogging and anaerobic conditions within soils. I therefore hypothesised that redox potentials would be lower in areas of vehicle disturbance, due to localised depressions in the marsh surface that promote water-logging. I hypothesised that pH would not significantly vary between impact and control saltmarsh, as vehicle disturbance was not identified as a process likely to cause acidification or alkalisation.

Finally, I hypothesised that vehicle disturbance would be associated with changes to micro-topography and thus hydrology. This is likely to be in the form of depressions in the marsh surface from the weight of vehicle passage and erosive effects of moving tyres. As a result, I anticipated that these areas would experience changes to hydrology with water pooling in these areas after tidal inundation or precipitation.

1.3 Significance of research

Despite being considered a severe and rapidly escalating threat to saltmarsh ecosystems, studies on the impacts of off-road vehicles to saltmarsh are limited to a handful of studies (Wisheu & Keddy 1991; Blionis & Woodin 1999; Hannaford & Resh 1999; Howard et al. 2014b), and Australian studies are particularly limited (Kelleway 2005; Trave & Sheaves 2014). Current understanding of the impacts of in-situ physical disturbances to saltmarshes have focussed on vegetative, faunal and abiotic responses, and there is little knowledge of the impacts on the seed bank (Wisheu & Keddy 1991; Howard et al. 2014b). Furthermore, no prior studies (to my knowledge) have investigated the impacts of vehicle damage on the soil seed bank in Australian saltmarsh. Understanding the response of the seed bank to vehicle disturbance is important, because it offers insight into the potential for passive vegetation regeneration. Understanding abiotic responses to vehicle disturbance also has important implications for rehabilitation, as environmental conditions must be suitable for re-colonisation of vegetation. Overall, further scientific understanding of the impacts of off-road vehicles to saltmarsh is required to inform effective rehabilitation efforts. Investigation of vegetative, seed bank and abiotic responses to vehicle disturbance on South Coast saltmarsh sites, will address key knowledge gaps and provide important information for potential rehabilitation strategies.

1.4 Thesis structure

Chapter 1 has established the context of the study, outlined the projects research aims and identified key knowledge gaps regarding the impacts of vehicle disturbance to saltmarsh. Chapter 2 assesses the relevant literature and reviews the current scientific understanding of; the geomorphic and ecological components of saltmarsh environments (Section 1), anthropogenic impacts on saltmarsh including vehicle disturbance (Section 2) and saltmarsh management and rehabilitation (Section 3). Chapter 3 outlines the methods applied in this study, including an overview of the study locations, experimental design and data analysis. Chapter 4 presents the results of the study. Chapter 5 discusses the key findings of this research, highlights areas of research requiring further work and provides management recommendations. Chapter 6 summarises the major findings of the present study.

2 Literature Review

2.1 Saltmarsh ecosystems: an overview of geomorphic and ecological components

Saltmarsh ecosystems are found on many of the world's coastlines and their nature depends on a range of factors; such as climate, hydrology, sediment characteristics, tidal range, local flora and fauna, current and wave energy, topography and stability of the coastline (Frey & Basan 1978). The world's saltmarshes can be grouped into major biogeographical classes, based on community and species distributions (Chapman 1960; Adam 1990). Australian saltmarshes fall within temperate and tropical bioregions and saltmarsh on the south-eastern coastline is regarded as temperate (Adam 1990). Saltmarsh in south-eastern Australia is restricted to estuarine environments and the geomorphic condition of these estuaries has significant influence on wetland ecology (Roy et al. 2001).

2.1.1 Estuaries

An estuary is an inlet of the sea that reaches inland (Woodroffe 2002). The NSW Estuary Management Manual (NSW Govt. 1992) defines an estuary as "any semi-enclosed body of water having an open or intermittently open connection with the ocean, in which water levels vary in a predictable, periodic way in response to the ocean tide at the entrance".

Estuaries can be divided into various zones with different water quality properties, habitat characteristics and depositional environments (Roy et al. 2001). Roy et al. (2001) identified four geomorphic zones with distinct hydrological and biological attributes within all south-east Australian estuaries. These zones ordered from seaward to landward include a marine flood-tidal delta, central mud basin, fluvial delta and riverine and alluvial plain (Roy et al. 2001). Environments associated with each zone range from shallow subtidal, through intertidal to terrestrial. Salinity and temperatures also vary with river flow, tidal exchange and intertidal exposure (Roy et al. 2001). Table 1, adapted from Roy et al. (2001), outlines the sub-environments, hydrology and substrate characteristics associated with each geomorphic zone.

Table 1: Estuarine geomorphic zones and associated properties (Roy et al. 2001).

Geomorphic Zone	Properties				
	Main sediment types	Annual salinity range (ppt)	Annual temperature range (°C)	Total phosphorous (µg 1^{-1})	Nitrogen concentration (µg 1^{-1})
Marine tidal delta	Quartzose and muddy sand	30-35	5	20-23	<25
Central mud basin	Organic-rich and sandy mud	20-30	7	30-80	<25
Fluvial delta	Sandy mud and muddy sand	10-20	10	15-50	100
Riverine channel	Fluvial and muddy sand	<10	10-15	10-25	500

Roy et al. (2001) provided the most widely used estuary classification scheme in NSW. Coastal water bodies in New South Wales were classified based on two conditions; location within various coastal settings and their geomorphological evolution, which depends on differing rates of sediment infill (Roy 1984). Although this scheme is based on physical attributes, it also provides a framework for characterising estuarine ecology (Roy et al. 2001).

Roy et al. (2001) classification of coastal water bodies in eastern Australia, formed from the inheritance of different geologic and geomorphic settings, is outlined in Table 2, including types and examples for each group. Four main estuary types in NSW are visually represented in Figure 3, adapted from Roy et al. (2001).

Table 2: Roy et al. (2001) classification scheme for coastal water bodies including types and examples for each group

Groups	Types	Examples
I. Bays	1. Ocean Embayments	Botany Bay
II. Tide-dominated estuaries	2. Funnel-shaped macrotidal estuary	South Alligator River, Northern Territory
	3. Drowned river valleys	Hawkesbury River
	4. Tidal basin	Moreton Bay
III. Wave-dominated estuaries	5. Barrier estuary	Lake Macquarie
	6. Barrier Lagoon	The Broadwater/ South Stradbroke Island
	7. Interbarrier estuary	Tigerlilly Creek
IV. Intermittent estuaries	8. Saline coastal lagoons	Smiths Lake
	9. Small coastal creeks	Dalhousie Creek
	10. Evaporative lagoons	The Coorong
V. Freshwater bodies	11. Brackish Barrier	Myall Lakes
	12. Perched dune lake	Lake Hiawatha
	13. Backswamp	Everlasting Swamp, Clarence River

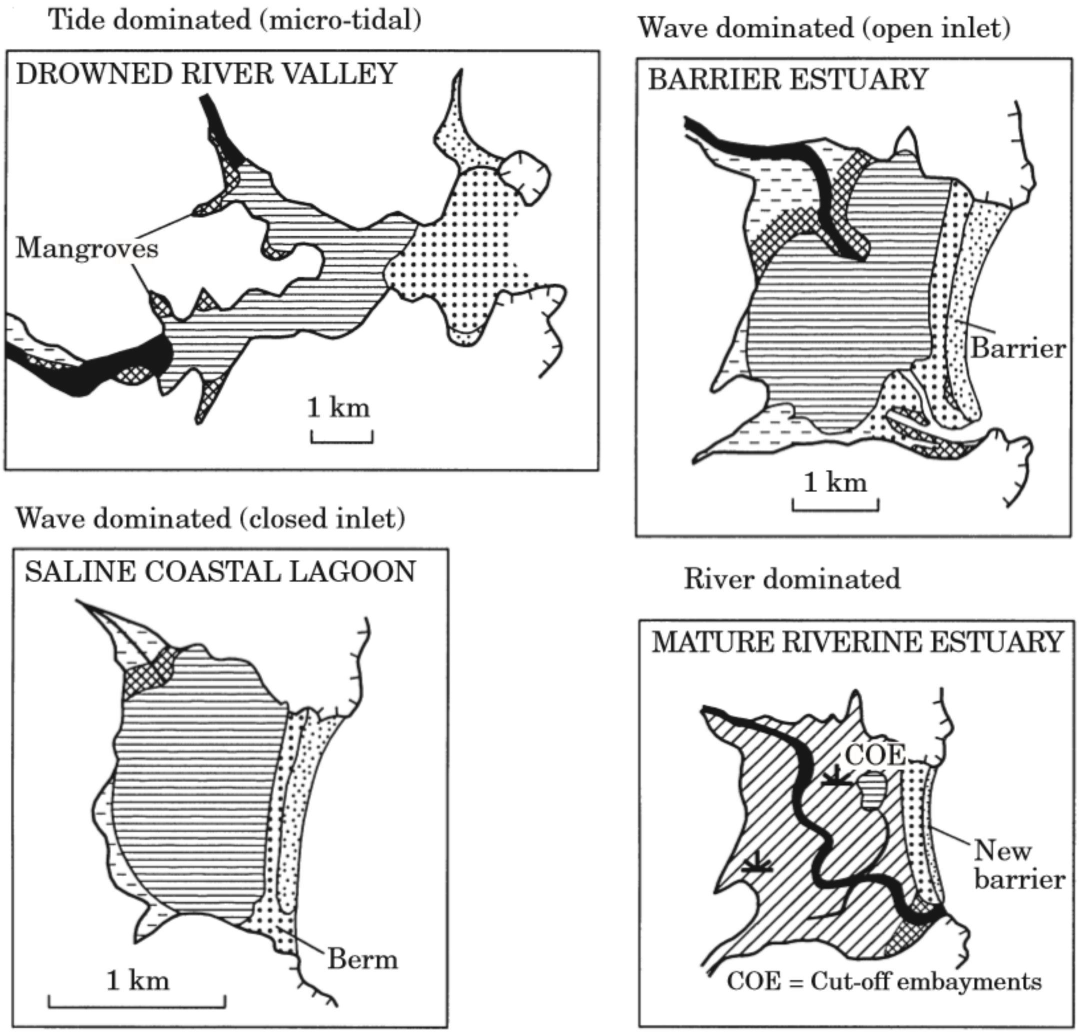

Figure 3: Major estuary morphologies of the NSW coast, adapted from Roy et al. (2001)

With sufficient time, stable sea level and continuous sediment supply, estuaries will infill and convert estuarine water areas to terrestrial floodplains, levees and backswamps (Roy et al. 2001; Harris & Heap 2003). Roy et al. (2001) adopted a four stage scheme to represent estuarine succession from relatively unfilled estuaries to mature infilled estuaries, exhibited in Table 3.

Table 3: Roy et al. (2001) stages of estuarine succession. NSW examples provided by Roper et al. (2011)

Stage	**Description**	**Estuarine infill (%)**	**NSW Examples**
A	Youthful or Immature	0-25	Smiths Lake, Lake Macquarie
B	Intermediate	25-50	Parramatta River, Lake Illawarra.
C	Semi-mature	50-75	Currambene Creek, Bermagui River
D	Mature	> 75	Minnamurra River, Tomaga River

An alternate classification scheme that has also been widely adopted in Australia, was provided by Heap et al. (2001). This ternary scheme categorizes Australian coastal water bodies by the relative influence of wave, tide and river energies (Boyd et al. 1992; Dalrymple et al. 1992; Heap et al. 2001) as shown in Figure 4.

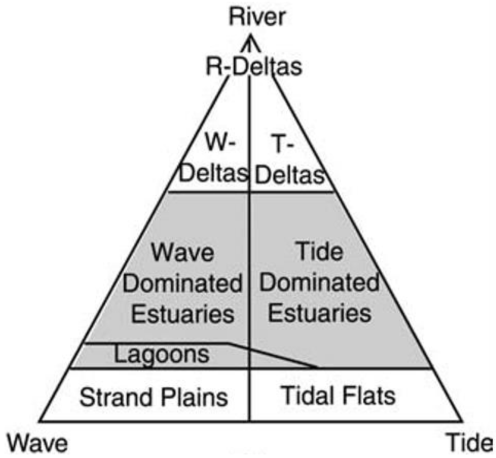

Figure 4: Ternary scheme classifying Australian coastal water bodies (Heap et al. 2001)

2.1.2 Estuarine saltmarsh development

The majority of estuaries on the south-east Australian coast are wave-dominated barrier estuaries in various stages of geomorphological evolution (Roy et al. 2001). These estuaries are characterised by tidal inlets that are constricted by wave deposited sand and relatively small flood-tidal deltas (Roy et al. 2001). Tidal ranges within these estuaries are considerably less than ocean tidal ranges and are more heavily influenced by river discharge than marine influences (Roy et al. 2001). In these environments, saltmarsh occupation is usually limited to the central mud basin where low energy conditions occur (Harris & Heap 2003; Saintilan & Rogers 2013). Although saltmarsh is a feature common to all barrier estuaries in NSW, the degree of saltmarsh development varies considerably (Saintilan et al. 2009). Barrier estuaries that are intermittently closed are termed coastal lagoons or ICOLLs (Intermittently Closed and Open Lakes and Lagoons). When the ICOLL entrance is closed or more intermittently closed, the tidal range is restricted (Saintilan et al. 2009; Saintilan & Rogers 2013). These conditions may be sufficient to elevate the estuary waters above the level of mangrove pneumatophores, preventing their growth or causing widespread dieback (Saintilan et al. 2009; Saintilan & Rogers 2013). Under these conditions, saltmarsh can dominate over mangrove communities (Saintilan et al. 2009; Saintilan & Rogers 2013).

Tide dominated estuaries are typified by large entrances and large tidal ranges similar to the open ocean (Roy et al. 2001). On the high wave energy coast of south-eastern Australia, tide dominated estuaries are usually the result of particular coastal settings that subdue wave action (Roy et al. 2001). Drowned river valleys are classed as tide dominated estuaries and in NSW they occur along the central coast and Batemans Bay in association with the Lachlan Orogen (Roy et al. 2001; Saintilan & Rogers 2013). These estuaries usually receive inputs from large coastal rivers and provide a range of environments suitable for saltmarsh development (Saintilan et al. 2009). Saltmarsh occurs within drowned river valleys on the meandering fluvial channel where tidal influence is significantly reduced. Saltmarsh in these tide dominated estuaries is also found on fluvial deltas, the upper intertidal zone of cut-off embayments and on back-barrier sands near the estuary mouth (Saintilan et al. 2009; Saintilan & Rogers 2013).

2.1.3 Tides and salinity

Coastal saltmarshes occur where soil salinities are elevated, which is most commonly associated with tidal inundation (Adam 1990). Tidal regimes and ranges vary considerably around the Australian coastline (Adam 2009). Tides on the east coast are predominantly semi-diurnal, meaning they experience two high tides and two low tides per day (Adam 2009). The tidal range is mostly low (micro to meso-tidal) in southern Australia, but can be amplified in bays and inlets (Adam 2009). Saltmarsh environments occur in the upper intertidal zone, generally between mean high tide and mean spring tide on mainland Australia (Saintilan et al. 2009).The lateral extent of saltmarsh is dependent on local topography and geomorphology (Saintilan et al. 2009).

In the lower marsh, tidal inundation is frequent and thus the soil salinity is relatively constant (Adam 1990). At higher elevations, salinities can vary considerably due to the enhanced influence of climate and flooding (Adam 1990). Between periods of tidal flooding, rainfall will reduce soil salinity whereas in drier periods evapotranspiration will increase salinity (Adam 1990). Tidal submergence also results in waterlogged and anaerobic soils, although the duration of waterlogging will depend on the local hydrology (Adam 2009).

2.1.4 Saltmarsh flora

Three categories of saltmarsh vegetation can be distinguished based on their dominant growth form: (1) herb communities, (2) communities dominated by grasses, sedges and rushes and (3) dwarf shrub communities (Adam 1990). Saltmarsh is distinguished from other vegetation types found in similar habitats by its floristic composition and structure (Adam 1990; Adam 2009). Mangrove communities are distinct from saltmarsh due to the dominance of trees. Seagrass beds are predominantly submerged and dominated by various monocots (Adam 1990; Adam 2009).

Saltmarsh vegetation must be tolerant of extreme ranges of salinity and soil water content (Saintilan 2009). Saltmarsh plants are halophytic, meaning they are able to complete their lifecycle in saline conditions (Jennings 1976; Adam 1990). Saltmarsh plants can reproduce sexually, by flowering and dispersing seeds, or vegetatively, by cloning or spreading of plant parts into new areas (Laegdsgaard 2006). Along with tolerance of saline soils, saltmarsh plants must also withstand periodic inundation (Saintilan 2009). Tidal flows may dislodge seedlings, meaning that extended periods of time between inundation may be required for germination and development of robust seedlings (Adam 2009). Flooding from turbid estuarine water can also lead to a reduction in photosynthesis, as vegetation may become coated in sediment (Adam 2009). Furthermore, inundation may also alter the effective day length and expose plants to a sudden temperature shock (Adam 2009).

The interaction between environmental factors such as tidal flows and salinity often leads to a zonation of vegetation species and communities that reflect hydro-period (Laegdsgaard 2006; Adam 2009; Saintilan 2009). The zones are generally described as the lower, mid and upper marsh (Laegdsgaard 2006). In general, species diversity is higher in the upper marsh levels (Adam 1990; Adam 2009). Vegetation zonation trends are often complicated by small-scale patchiness with the occurrence of community mosaics rather than a band of a single community (Zedler et al. 1995). The vegetation mosaic reflects local micro-topography and drainage conditions (Zedler et al. 1995; Adam 2009). In NSW, the lower marsh zone is generally dominated by herbs and grasses and the mid to upper marsh is dominated by sedges and rushes (Saintilan 2009). While numerous plant species can be found within south-east Australian saltmarsh, only a few species dominate. Descriptions of the dominant NSW saltmarsh species are presented in Table 4.

Table 4: Dominant saltmarsh species of south eastern NSW (Clarke & Hannon 1970; Adam 1981; Saintilan 2009)

Name	**Common Name**	**Family**	**Description**
Sporobolus virginicus	Saltwater couch, Sand Couch, Nioaka	Poaceae	*Sporobolus virginicus* is the most widely distributed saltmarsh plant in Australia. (Adam 1981; Saintilan 2009). It has a high tolerance of waterlogged acidic soils and grows particularly well in sandy locations (Adam 1981; Saintilan 2009). Its seeds are predominantly airborne but can be dispersed by water (Naidoo & Naidoo 1992). The species is found scattered in most saltmarsh communities but may also form extensive pure stands which occupy large areas (Adam 1981).
Sarcocornia quinqueflora	Samphire, Beaded Glasswort	Chenopodiaceae	*Sarcocornia quinqueflora* is the dominant saltmarsh species in southern and central NSW (Saintilan 2009). The species is a herb which forms a creeping mat, and its colour ranges from green to red and purple (Adam 1981). The low growing plant occurs in wetter conditions and is often the only vascular plant in the lower saltmarsh (Adam 1981).
Juncus kraussii	Sea Rush	Juncaceae	*Juncus kraussii* is a tall rush which forms thick stands generally less than a metre high (Saintilan 2009). The species grows in fresher conditions than *Sporobolus virginicus* and *Sarcocornia quinqueflora* and is often the dominant community in the upper marsh (Adam 1981; Saintilan 2009). *Juncus kraussii* can withstand several months of continuous inundation on the margins of brackish lagoons (Adam 1981).
Samolus repens	Creeping Brookweed	Theophrastaceae	*Samolus Repens* is widespread in south east Australia but rarely forms a dominant stand (Saintilan 2009). The species is a low-growing herb that produces small white or pink flowers between September and March (Saintilan 2009).
Suaeda australis	Seablite	Chenopodiaceae	*Suada australis* is a small, woody upright perennial herb. It has succulent leaves and is taller than the other common chenopod, *Sarcocornia quinqueflora.* It is common throughout the east Australian coast but is usually only found in small patches. The species favours relatively drier, better drained conditions than *Sarcocornia quinqueflora,* but relies on water for seed dispersal (Clarke & Hannon 1970).
Triglochin striata	Streaked arrowgrass	Jungaginaceae	*Triglochin striata* consists of erect leaves most commonly 10 cm long, often in groups of 3 (Saintilan 2009). The three-ribbed or streaked arrowgrass is common in slight depressions of the saltmarsh with impeded drainage (Adam 1981; Saintilan 2009). The species is widely distributed in Australia and other southern continents (Adam 1981).

Saltmarsh vegetation on the south-eastern coastline is ecologically significant, due to its high level of species diversity. Australian saltmarsh species diversity increases with increasing latitude, contrasting with mangrove diversity trends (Saenger et al. 1977; Specht 1981; Adam et al. 1988; Saintilan 2009). The southern States including New South Wales, Tasmania, Victoria, South Australia support 90% of Australian saltmarsh flora, despite comprising less than 2.5% of the total saltmarsh/saltpan area (Saintilan 2009). Saltmarsh species diversity in Northern Australia is comparatively low and this has been related to intolerance of higher temperatures, or intolerance of both higher temperatures and higher seasonal salinities (Greenwood & MacFarlane 2006; Saintilan 2009). Saltmarsh plants in southern NSW are also usually more diverse than northern NSW, with characteristic species (not listed in Table 4) such as *Austrostipa stipoides*, *Gahnia filum*, *Limonium australe* and *Sclerostegia arbuscular* (Hughes 2004). Rare and threatened plant species can also be found in southern NSW saltmarsh including *Wilsonia rotundifolia* (endangered) and *Wilsonia backhousei* (vulnerable).

2.1.5 The seed bank in saltmarsh soils

When seeds within soil remain dormant and viable, they form what is known as a soil seed bank (Leck 1989; Baskin & Baskin 1998). Seed banks influence population dynamics of the standing vegetation, because they comprise a large component of species available for recruitment (Leck 1989). Seed banks act as reservoirs for biodiversity and facilitate the persistence of sexually reproducing plant species (Vilà & Gimeno 2007). Seed bank composition (species and relative abundance) is influenced by dispersal capability of plants, plant pollinator interactions, reproductive output, propagule settlement and survival, and ability to be incorporated and stored in the soil (Leck 1989; Chambers & MacMahon 1994).

Plant seeds capable of remaining viable within soil, allow species to bridge unsuitable conditions for germination and establishment (Bossuyt & Honnay 2008). This capability reduces the risk of germination and growth in undesirable conditions and conserves population genetic variation over time (Bossuyt & Honnay 2008). The presence of viable seed provides a mechanism for recovery following destructive disturbance to standing vegetation (Lavorel et al. 1994; Kalamees & Zobel 2002). This has important implications for saltmarsh rehabilitation. For example, Lindig-Cisneros and Zedler (2002) found halophyte recruitment to be low in saltmarsh rehabilitation sites where the substrate lacks a seed bank and dispersal from natural wetlands was limited.

In estuarine environments, halophytic plants form a seed bank by producing seeds that can remain dormant within the soil (Ungar 1991). These seeds can tolerate periodic inundation as well as soil that is often dense, oxygen deficient and highly saline (Leck 1989; Ungar 1991). Seed establishment is the primary mechanism by which many saltmarsh species colonise new areas, although many species also spread vegetatively, flower and set seed infrequently (Adam 1990). Abiotic conditions within the saltmarsh, such as high salinity, can reduce germination of some seeds (Greenwood & MacFarlane 2006; Green et al. 2009). For example, Greenwood and MacFarlane (2006) found salinity affected germination of *Juncus kraussi*, which had 100% germination in fresh water experiments but failed to germinate in 30 ppt saline water. Furthermore, Green et al. (2009) found increased germination rates of *Suaeda australis* and *Sarcocornia quinqueflora* following high rainfall events in a rehabilitated marsh in Northern NSW. However, without influxes of saltwater tides, seeds are unlikely to be dispersed and thus colonise new areas (Huiskes et al. 1995). Therefore, saltmarsh species rely on interactions between tides and precipitation for seed dispersal and germination.

Saltmarsh seed bank studies have generally focussed on density and composition of the seed bank, and compared these variables to above ground vegetation, e.g. (Milton 1939; Hopkins & Parker 1984; Egan & Ungar 2000; Wolters & Bakker 2002). A common finding from these studies is that the seed banks of saltmarsh tend to be floristically diverse but overall dominated by a few key species (Hopkins & Parker 1984; Marañón 1998; Morzaria-Luna & Zedler 2007; Murphy 2014). However, the density of seed and relationship between seed bank variables and above ground vegetation varies considerably between studies e.g. (Milton 1939; Hopkins & Parker 1984; Egan & Ungar 2000; Wolters & Bakker 2002). Murphy (2014) studied estuarine seed bank complexes at three locations on the South Coast of NSW. Murphy (2014) found that saltmarsh seed banks were highly dense with approximately 4000 seeds/m^2. However, there was a high level of spatial variation within sites suggesting that the density of saltmarsh seed banks is not uniform (Murphy 2014). Consistent with the findings of Morzaria-Luna and Zedler (2007), Murphy (2014) found that all above ground saltmarsh species were represented in the seed bank. This indicated that the seed bank plays an important role in maintaining the characteristic structure of saltmarsh and may be a vital source of seed in the case of large-scale vegetation loss (Murphy 2014).

2.1.6 Importance of saltmarsh for habitat and ecosystem services

Saltmarsh provides habitat for a diverse range of fauna, ranging from terrestrial to marine with some specialised saltmarsh dwellers (Laegdsgaard 2006). Fish contribute significantly to the biodiversity of Australian saltmarsh systems. During the spring high tide, fish and swimming crustaceans are able to disperse over the main marsh surface (Connolly 2009). Molluscan fauna including gastropods and bivalves live on (i.e. epifauna) or in (i.e. infauna) the saltmarsh sediment (Ross et al. 2009). Crabs are also play important roles within saltmarshes, as they influence ecosystem function by modifying the physical structure of the sediment (Mazumder 2009). Saltmarshes also provide habitat for pestiferous and vector mosquitoes such as *Ochlerotatus vigilax* (Ryan et al. 2000; Laegdsgaard 2006). For many avian species, saltmarsh is of direct importance because it provides habitat for individuals to feed, breed and roost (Spencer et al. 2009). Migratory bird species found in Australia take a route known as the East Asian-Australasian flyaway and spend their non-breeding seasons in Australia from September to April (Spencer et al. 2009). As signatories to international agreements that endeavour to maintain migratory shorebird habitat, the preservation of saltmarsh habitat should be of high importance (Saintilan & Rogers 2013). Australian saltmarsh provides habitat for a range of vertebrate species, including insectivorous bats (Laegdsgaard 2006; Spencer et al. 2009), macropods such as the Eastern Grey Kangaroo (*Macropus giganteus*) and the Swamp Wallaby (*Wallabia bicolor*) and reptilian and amphibian species such as goannas and monitors (*Varanus* species), the red bellied black snake (*Psuedechis porphyriacus*) and the golden bell frog (*Litoria aurea)* (Spencer et al. 2009).

Coastal wetlands, including saltmarsh ecosystems, provide a range of highly valued ecosystem services (Costanza et al. 1989; Barbier et al. 1997; Farber et al. 2006). Saltmarsh protects the coastal zone, as a buffer between terrestrial and aquatic environments (Costanza et al. 2008). Wetland communities including saltmarsh protect estuarine foreshores by storing storm energy and minimising erosion (Costanza et al. 2008). Saltmarsh environments trap and stabilise sediment, moderate the impacts of floodwaters and maintain water quality by trapping contaminated runoff from rural and urban areas (Chenhall et al. 1992; Koch et al. 2009). Saltmarsh as a form of coastal protection will become increasingly important with projected sea level rise and increased storm surge intensity associated with climate change (Gedan et al. 2011).

The term ‘Blue Carbon’ refers to carbon captured and stored by marine and coastal ecosystems, primarily mangrove, saltmarsh and seagrass (Mcleod et al. 2011). These ecosystems are extremely efficient at sequestering carbon, contributing much more per unit area to long term sequestration than terrestrial habitats (Mcleod et al. 2011). Coastal wetlands are highly efficient carbon sinks because methane emissions are significantly reduced in saline environments (Poffenbarger et al. 2011). Additionally, these environments are effective at trapping suspended matter and associated organic carbon during tidal inundation (Mcleod et al. 2011). As efforts to reduce the impacts of rising CO_2 become more widespread, conservation and rehabilitation of natural carbon sinks such as saltmarsh should be highly prioritised (Mcleod et al. 2011).

2.2 Saltmarsh: Anthropogenic Impacts

2.2.1 Legislation and management frameworks

Saltmarsh in Australia and New South Wales is highly protected under various national, State and local legislation and planning frameworks. Relevant regulatory frameworks and their implications for saltmarsh environments are outlined in Table 5.

Table 5: Federal and State (NSW) regulatory frameworks the offer protection to coastal saltmarsh

Government Level	Legislation	Implications for saltmarsh
Federal	*Environment Protection and Biodiversity Conservation Act* 1999 (EPBC Act)	The EPBC Act provides a legal framework to protect and manage national and internationally significant fauna, flora, heritage places and ecological communities. Sub-tropical and temperate coastal saltmarsh is listed as vulnerable under the EPBC Act (Department of the Environment 2013). The EPBC Act also incorporates the Convention on Wetlands of International Importance (Ramsar Convention) (Rogers et al. 2016). Ramsar wetlands in Australia include 19 mangrove and saltmarsh wetlands and their protection is largely based on function as waterbird or fish habitat (Rogers et al. 2016).
State	*Threatened Species Conservation Act* 1995 (TSC Act)	Specific saltmarsh legislation in NSW includes the 2004 declaration of coastal saltmarsh in the NSW North Coast, Sydney Basin and South East Corner bioregions as an 'Ecologically Endangered Community' (EEC) under the *Threatened Species Conservation Act 1995* (TSC Act) (Hughes 2004). Several NSW saltmarsh plant species are listed as threatened species under the TSC Act including *Wilsonia rotundifolia* (endangered), *Distichlis distichophylla* (endangered) and *Wilsonia backhousei* (vulnerable). A licence is required under the TSC Act for actions that could damage saltmarsh or the habitat of any other threatened species, population or community that inhabits saltmarsh (Hughes 2004).
State	*Fisheries Management Act* 1994 (FM Act)	Saltmarsh is protected under the *Fisheries Management Act* 1994 (FM Act) due to the community's importance for fish habitat. Any development or activity (such as developments requiring approval under the Environmental and Planning Assessment Act 1979) that may harm saltmarsh must be approved by the NSW Department of Primary Industries (DPI) (Russel & Walsh 2015).
State	*State Environmental Planning Policy* (SEPP)	Many areas of coastal saltmarsh outside the Sydney Metropolitan area are listed under the State Environmental Planning Policy (SEPP) No. 14 – Coastal Wetlands. The policy applies to 1300 mapped wetlands of high natural value from Tweed Heads to Broken Bay and from Wollongong to Cape Howe. Any developments such as land clearing, drainage work, levee construction and filling on these wetlands requires the consent of local council and the agreement of the Department of Planning and Infrastructure (Russel & Walsh 2015). As part of a State wide coastal reform, SEPP 14 wetlands are proposed to include a 100m buffer area, that will permit natural changes in wetland extent and provide protection from the effects of surrounding development (Rogers et al. 2016).
State	*Marine Estate Management Act 2014*	The *Marine Estate Management Act* 2014 provides for management of all NSW marine waters, the coastline and estuaries up to the HAT, including saltmarsh. The Act includes a formalised threat and risk assessment based approach for managing the marine estate areas (Russel & Walsh 2015).

2.2.2 Threats to saltmarsh

Coastal saltmarshes in Australia and throughout the world, have experienced severe degradation, with many areas ‘reclaimed’ for agricultural, industrial and residential purposes (Kelleway & Williams 2008; Laegdsgaard et al. 2009). Despite its status as a threatened ecological community throughout Australia and globally (Adam 2002; Rogers et al. 2016), saltmarsh structure and ecological function continues to deteriorate at a rapid rate, due to anthropogenic disturbances. These large-scale losses can be attributed to a lack of information on the ecological importance of saltmarsh systems (Laegdsgaard 2006). Although their significance has been widely realised in more recent years, numerous activities detrimental to saltmarsh continue to occur (Laegdsgaard 2006). Past, present and emerging processes that threaten saltmarsh are outlined below.

Climate Change

Saltmarsh ecosystems in Australia are expected to be affected by environmental changes brought on by increased atmospheric carbon (Saintilan & Rogers 2013). Considering the high levels of saltmarsh plant diversity in more southern, cooler parts of Australia, increased temperatures may threaten the survival of a number of species. Significant warming may negatively impact some cold-dependent species and further promote the spread of mangroves (Saintilan & Rogers 2013). Increased atmospheric carbon is likely to favour the growth of mangroves, especially in low salinity environments (Ball et al. 1997; Saintilan & Rogers 2013). Rising sea levels associated with climate change also threaten saltmarsh as communities are likely to be forced to higher elevations (Kelleway & Williams 2008). Local geomorphology and the presence of anthropogenic structures such as seawalls, roads and buildings may limit the distribution of saltmarsh in response to sea level rise (Kelleway & Williams 2008).

Altered hydrology

As part of urban and agricultural development and reclamation, hydrology and drainage conditions have been altered in many saltmarsh environments. Such changes have led to severe damage to saltmarsh communities, with impacts ranging from habitat destruction to modification of ecosystem function (Laegdsgaard 2006). Removal of tidal influence through the construction of levee banks can lead to an increase in water levels due to freshwater run-off (Laegdsgaard 2006). This can lead to the inundation of saltmarsh for extended periods of time, which can be detrimental to certain plants such as *Sarcocornia quiqueflora* that can only withstand short periods of submergence (Adams & Bate 1994). Furthermore, artificial tidal barriers can lead to a lowering of the water table and a relative drop in saltmarsh surface elevation (Laegdsgaard 2006).

Fragmentation

The separation of large saltmarsh expanses into smaller areas and the disconnection of saltmarsh from surrounding estuarine habitats is a major cause of habitat decline (Adam 2002). Residential, agricultural and industrial expansion has greatly reduced the extent of many saltmarshes, which is further compounded by bisecting roads and other anthropogenic structures in the vicinity. Decreased saltmarsh patch sizes are likely to impact foodweb dynamics, with rare and specialised species being the most vulnerable (Laedgsaard et al. 2009).

Mangrove incursion

Mangrove incursion into saltmarsh environments has been widely documented in many estuaries throughout south-east Australia (Saintilan & Williams 1999). Saintilan and Williams (1999) suggested a number of mechanisms to explain this phenomenon which included increased annual precipitation, recolonisation of areas damaged by agricultural practices, altered tidal regimes, increased sediment and nutrient inputs and subsidence of intertidal surfaces. Mangroves are recognised as being of high conservation value and their dispersal into saltmarsh causes a number of complex management issues (Adam 2002). Mangroves are protected under the Fisheries Management Act (1994), which means endeavours to remove mangroves from saltmarsh areas requires approval under NSW legislation (Adam 2002).

Invasive species

Invasion of exotic plant species threaten saltmarsh ecosystems throughout the world, with the potential to become widespread and displace native plants (Adam 2002; Laegdsgaard 2006). One of the most significant invasive plants threatening Australian saltmarsh is *Juncus acutus*, which is native to the Mediterranean. This species has become widespread throughout eastern Australia, by displacing the native *Juncus kraussii* and altering the complexity of affected communities. Other exotic species jeopardising saltmarsh in eastern Australia include *Baccharis hamifolia, Spartina anglica, Cortaderia selloana* and *Hydrocotyle bonariensis* (Laegdsgaard 2006; Daly 2013).

Agriculture

Where agricultural areas encroach upon saltmarsh, pasture species are able to invade and outcompete saltmarsh vegetation, until pasture grasses can no longer tolerate salinity levels (Laegdsgaard 2006). In addition to increased competition, many saltmarsh areas are used as pasture for livestock. This exposes saltmarsh plants to grazing and trampling from hard hooved animals which can disrupt the dense vegetation and root systems of plants and promote tidal pooling (Zedler et al. 1995; Laegdsgaard 2006). Other plant species more tolerant of waterlogging and lower salinities may colonise these areas in response to the changed conditions (Zedler et al. 1995). Furthermore, livestock may selectively graze saltmarsh plants, which leads to a change in typical saltmarsh species distributions (Zedler et al. 1995).

Urbanisation

In addition to fragmentation of the saltmarsh landscape, urbanisation is associated with a number of other threatening processes. Mowing and watering of saltmarsh with freshwater can occur when communities are close to urban development, which can damage succulent species and disrupt the flowering of grasses (Laegdsgaard et al. 2009). Watering of lawns adjacent to saltmarsh decreases salinity and reduces saltmarsh species' competitive advantage. This can lead to invasion by terrestrial grass species and common garden plants. Litter dumping is another common problem encountered in urban saltmarshes. Dumped garden waste is particularly concerning in saltmarsh because it can lead to the introduction of weeds (Laegdsgaard 2006). Urban development in close proximity to saltmarsh also causes problems relating to stormwater discharge. Stormwater discharge may alter salinity and nutrient conditions within saltmarsh, which has led to mangrove colonisation in parts of NSW (Saintilan & Williams 1999) and may promote the spread of freshwater and brackish species (Laegdsgaard et al. 2009). Runoff from adjacent roads and tracks can also increase pollutant loads within the saltmarsh environment (Adam 2002).

2.3 Impacts of vehicle passage

The use of off-road vehicles in natural environments can cause significant damage, especially in ecosystems sensitive to physical disturbance. Detrimental impacts of off-road vehicles have been investigated for a range of different environments, with particular focus on desert, beach and cold climate ecosystems (tundra, alpine) (e.g. Ahlstrand & Racine 1993; Priskin 2003; Schlacher et al. 2008; Schlacher & Thompson 2008; Webb & Wilshire 2012). The most common consequences of off-road vehicle usage in sensitive communities include damage to vegetation, such as loss of height, biomass reduction, cover reduction and shifts in species composition (Pickering & Hill 2007). Off-road vehicles can also be associated with changes to hydrology, changes to soil conditions including altered nutrient levels, erosion and the introduction of exotic weeds and pathogens (Pickering & Hill 2007).

In many parts of Australia, degradation and loss of saltmarsh area has been directly attributed to the use of off-road vehicles (Kirkpatrick & Glasby 1981; Kelleway 2005; Green et al. 2009; Trave & Sheaves 2014). Off-road vehicles include mountain bicycles, 4-wheel drive (4WD) vehicles and trail motorbikes. Kelleway (2005) estimated that over 2.1 ha of saltmarsh along the George's River had been damaged by vehicle use. Other NSW locations with evidence of vehicle damage to saltmarsh include (but are not limited to) Tweed Heads (Green et al. 2009) Bermagui, Tomakin, Batemans Bay, Hooka Point and Wapengo (K. Sampson 2016, pers. comm). The spatial extent of vehicle damage to saltmarsh in NSW and other parts of Australia is not known. Despite being considered a very serious and rapidly escalating threat throughout Australia and other parts of the world, only a handful of studies have exclusively investigated the impacts of off-road vehicles on saltmarsh communities (Wisheu & Keddy 1991; Blionis & Woodin 1999; Kelleway 2005; Howard et al. 2014b; Trave & Sheaves 2014).

2.3.1 Impacts of vehicle passage on saltmarsh

Table 6 presents a summary of all the studies that have examined the impacts of vehicles on saltmarsh ecosystems. Vehicle passage within saltmarsh environments is most widely associated with adverse impacts on vegetation communities. These impacts include reduced vegetation and dominant species cover (Blionis & Woodin 1999; Kelleway 2005), reduced biomass and vegetation height (Hannaford & Resh 1999; Howard et al. 2014b) and lowered plant productivity (Hannaford & Resh 1999). Vehicle disturbance has also been associated with changes to vegetation community composition, such as higher occurrences of typical lower marsh species and plants in early successional phases (Blionis & Woodin 1999; Kelleway 2005). Studies on the impacts of saltmarsh fauna are limited to crab and mollusc species; and have found reductions in the number of crab burrows in association with vehicle passage (Kelleway 2005; Trave & Sheaves 2014). The most commonly identified environmental change associated with vehicle disturbance in saltmarsh ecosystems, is increased soil compaction, indicated by bulk density and penetration to resistance (Blionis & Woodin 1999; Kelleway 2005; Trave & Sheaves 2014). Other environmental impacts include localised changes to micro-topography and hydrology (Kelleway 2005) and changes to soil properties such as reduced soil moisture and organic content (Blionis & Woodin 1999; Kelleway 2005).

Table 6: Summary table of all the studies that have investigated the impacts of vehicle disturbance on saltmarsh ecosystems

Author (Year) Location Marsh description	Aim of study	Disturbance mechanism	Variables used to measure disturbance	Key Findings
Blionis and Woodin (1999) Culbin Sands, north east Scotland Coastal marsh dominated by *Puccinellia maritima* and *Festuca rubra*	To assess the recovery of saltmarsh vegetation in relatively recent vehicle tracks and to relate vegetation change to the physical effects of vehicle tracks on the substratum.	Deep tracks in the saltmarsh were formed by tractors and other vehicles and were approximately 3 years old when studied.	Variables were compared between areas inside and outside the vehicle tracks. Variables included; - Soil compactions (penetration at four different depths) - Bulk density - Moisture content - Soil salinity - Frequency and abundance of vegetation species	Soil penetration resistance and bulk density was significantly greater in areas inside the track than in surrounding soil. Salinity and moisture content was lower within tracks. The organic layer present in surrounding vegetation communities, was severely reduced in vehicle damaged areas. Lower marsh species increased in vehicle tracks and higher marsh species declined. Vegetation inside tracks appeared to be in earlier successional phases than the surrounding vegetation, especially in lower marsh areas.
Hannaford and Resh (1999) San Francisco Bay, USA Coastal marsh dominated by *Salicornia virginica*	To determine the short and long-term effects of all-terrain vehicles (ATV's) on marsh vegetation.	Use of amphibious ATV's for wetland management.	A BACI experimental design was employed and variables were assessed before, immediately and one year after vehicle disturbance. Variables included; - Plant height and biomass of broken stems - Plant biomass and growth The study investigated the impacts of two types of ATV's with different sizes and weights. The impacts of light and heavy ATV use were also compared.	Stem height was significantly reduced immediately after ATV use and the impacts were similar for both heavy and light vehicle usage and both vehicle types. ATV use reduced biomass of *Salicornia virginica* immediately after usage for both vehicle types, with significantly more damage in areas where heavy vehicle usage occurred. After one year, lower stem height and lower productivity was only evident in areas that experienced heavy usage by the larger type of ATV (Hannaford & Resh 1999).

Howard et al. (2014b) Louisiana, USA Two coastal marshes dominated by *Spartina patens*	To describe the impacts of seismic exploration on marsh plant communities and soil seed bank. The study also aimed to document the ability of marsh to recover from exploration disturbance.	Disturbance from seismic surveys involved frequent vehicle passes by airboat or marsh buggy. Other activities included drilling holes and use of helicopters for transporting equipment.	A BACI (Before-After-Control-Impact) experimental design was employed which involved assessment before, 6 weeks after and every three months thereafter for 2 years. Variables included; - Plant species composition, percent cover and maximum height - Salinity, specific conductivity, temperature and pH of interstitial soil water - Salinity and specific conductivity of standing water above the marsh surface - Organic content matter and bulk density of marsh soil - Soil seedbank composition	Maximum vegetation height at impacted sites was reduced 6 weeks after disturbance for both marshes. A reduction in total vegetation cover and an increase in dead vegetation was found in impacted sites of one marsh 6 weeks after. These effects did not persist after 3 months. The number of seeds that germinated during the seedling emergence study increased at impact sites 5 months after the study for both marshes. Some seed bank impacts persisted for up to 1 year, but this was not reflected in the standing vegetation Soil and water properties were not impacted by disturbance.
Kelleway (2005) George's River, Sydney, NSW, Australia Temperate coastal saltmarsh dominated by *Sarcocornia quiqueflora* and *Juncus kraussi*	To quantify areas damaged by saltmarsh and to assess the associated ecological impacts	Kelleway (2005) estimated that 21 000 m^2 of saltmarsh in the George's River estuary has been impacted by recreational vehicles (BMX, mountain bikes, trail bikes and 4WD's) by 1998. Aerial photo analysis indicated that track networks extended out from naturally bare areas.	Variables were compared between impacted and non-impacted (control) areas. Variables included; - Cover of plant species, plant litter and algae - Number of plant seedlings, inhabited snail shells and crab burrows. - Soil properties including texture, compaction, bulk density and Electrical Conductivity (EC) Data were separated at the community level (*Juncus* or *Sarcocornia)* and track density level.	Total vegetation cover and dominant species cover in both plant communities decreased with increasing disturbance. Vegetation composition was altered by vehicle impacts which included the occasional increase of *Sporobolus virginicus* and *Sarcocornia quiqueflora* along the borders of some track areas in *Juncus* communities. Ground covering algae increased with increasing disturbance but was more prominent in Sarcocornia communities. Soil compaction was higher in disturbed sites than non-disturbed reference sites. For Sarcocornia communities, soil compaction increased significantly with each increase in disturbance level. This was not the case for *Juncus* communities. Only areas of high track density had significantly lower moisture contents than the undisturbed references site. In *Sarcocornia* communities, crab burrows and living molluscs decreased significantly with increases in track density. In *Juncus* communities, only crab abundance in low density track areas were significantly less than the undisturbed area.

Trave and Sheaves (2014) Townsville, QLD, Australia Tropcial saltmarsh dominated by *Sarcocornia quinquflora, Suaeda australis* and *Tecticornia indica*	To evaluate the impacts of vehicle passage on tropical saltmarsh ecosystems, with particular focus on the alteration of habitat for semi-terrestrial crabs.	The use recreational vehicles (BMX, trailbikes and quadbikes) in the areas had generated recognisable trails devoid of vegetation.	Variables were compared between areas at least 2 metres from the tracks, along the edge of the tracks and within the tracks. - Plant species presence/absence as an indication of species dominance and relative abundance - Abundance of crabs by manual capture, visual census and number of burrows - Soil compaction	At all sites crab burrows decreased from the undisturbed saltmarsh toward the car tracks, with areas within the tracks showing little or no evidence of crab burrows. However, no significant differences were found between the areas on the edge of the tracks and the undisturbed marsh. Soil compaction also increased from undisturbed to edge areas and again from edge areas to tracks.
Wisheu and Keddy (1991) Nova Scotia, Canada Atlantic coastal plains on two separate lakes. Study areas contained rare species (e.g. *Sabatia kennedyana)* and common rushes (*Juncus spp.).*	To describe the seed bank of a rare wetland community. The study also aimed to compare the seed bank to both the standing adult vegetation and to another coastal plain site disturbed by all-terrain vehicles.	Shorelines of the lakes studied are regularly used by all-terrain vehicles. At one of the lakes, vehicle usage has reduced Canada's largest stands of threatened *Sabaita kennedyana* by 90%.	Variables were compared between impacted and non-impacted (control) areas. Variables included; - Seed bank abundance and composition - Adult vegetation: standing vegetation and litter cover, species richness, weight of individual species (compared to seed bank but not directly compared between disturbed and undisturbed sites)	In undisturbed areas, soil seed banks were rich and averaged 8500 seeds/m^2. Seeds were most abundant at higher elevations where standing vegetation was greatest. Seed densities were much lower on an intensely disturbed shoreline, on average 1000 seeds/ m^2 Rare species made up 22% of standing vegetation and litter in undisturbed areas but comprised only 4% of the seed bank. Rushes including *Juncus canadensis* and *Juncus filiformis* were not abundant in the adult vegetation but were abundant in the seed bank. Wisheu and Keddy (1991) suggested that severe disturbances can destroy both standing vegetation and the seed bank. Moderate disturbances that do not completely destroy the seedbank will alter community composition whereby common rushes will replace rare species.

2.4 Saltmarsh Management and Rehabilitation

Increased awareness of saltmarsh as a highly valuable ecological community has led to an increase in rehabilitation efforts. Passive rehabilitation involves the removal of environmental stressors (e.g. off-road vehicles) to facilitate natural re-colonisation of flora and fauna species (McIver & Starr 2001; Morrison & Lindell 2011). In contrast, active rehabilitation involves management of the land to achieve a desired outcome and includes processes such as sediment profile restructuring or re-planting vegetation (McIver & Starr 2001). The Saltwater Wetlands Rehabilitation Manual by the NSW Department of Environment of Climate Change (2008) recommends implementing passive rehabilitation strategies where possible, before actively altering the wetland site (DECC 2008). Passive and active rehabilitation measures relevant to vehicle disturbance are outlined in this chapter.

2.4.1 Passive rehabilitation

Prohibit vehicle access

To effectively rehabilitate saltmarsh sites damaged by vehicle usage, access must be limited or completely denied where possible. Examples of saltmarsh areas that have been restricted by local authorities to facilitate remediation include the Bermagui Conservation Area in the Bega Valley LGA (K. Sampson 2016, pers. comm.) and the Kurnell Peninsula in the Sutherland Shire LGA (CT Environmental 2014). Fencing and removal of vehicles from the saltmarsh at Kurnell Peninsula was recognized as a major factor in the natural regeneration of *Sarcocornia quiqueflora* within damaged areas (CT Environmental 2014). In conjunction with fencing, planting of thick *Juncus kraussii* stands or *Casuarina glauca* trees across track entrance points and marsh edges may also discourage vehicle usage in saltmarsh (Kelleway 2005).

Education

Education initiatives that emphasise the value of saltmarsh can play an important role in minimising management threats, especially in areas close to urban development (Laegdsgaard et al. 2009). Such initiatives should highlight the importance of saltmarsh as habitat for a diverse range of fauna, as well as the vulnerability of vegetation to disturbances (Laegdsgaard et al. 2009). Education could be in the form of informational signage close to saltmarsh or along managed trails/board walks within saltmarsh environments (Laegdsgaard et al. 2009). Figure 5 is an example of educational signage highlighting the importance of saltmarsh, at Koona Bay, Lake Illawarra (DECC 2008). Educational signage should be placed in areas prone to vehicle damage; including areas where vehicle access has been restricted or in locations where vehicle prohibition is not practicable (Laegdsgaard et al. 2009). Signage could also include information on the laws pertaining to saltmarsh, such as the TSC Act (1995) or the FM Act (1994).

Introducing wetland education programs into community groups and local school curriculums may also be an effective long-term management solution for saltmarsh protection. The Hunter Wetlands Centre based in Shortland, on the Hunter River estuary, is an example of how wetland education can be used to promote long-term conservation goals (Maddock 1991; Hunter Wetlands Centre 2016). The Wetlands Centre is well equipped with facilities and resources for environmental education and provides formal school and non-formal adult programmes on site (Hunter Wetlands Centre 2016). Education programs have the capacity to highlight the importance of saltmarsh conservation and the appropriate protocol for using saltmarsh for recreational purposes (Laegdsgaard et al. 2009).

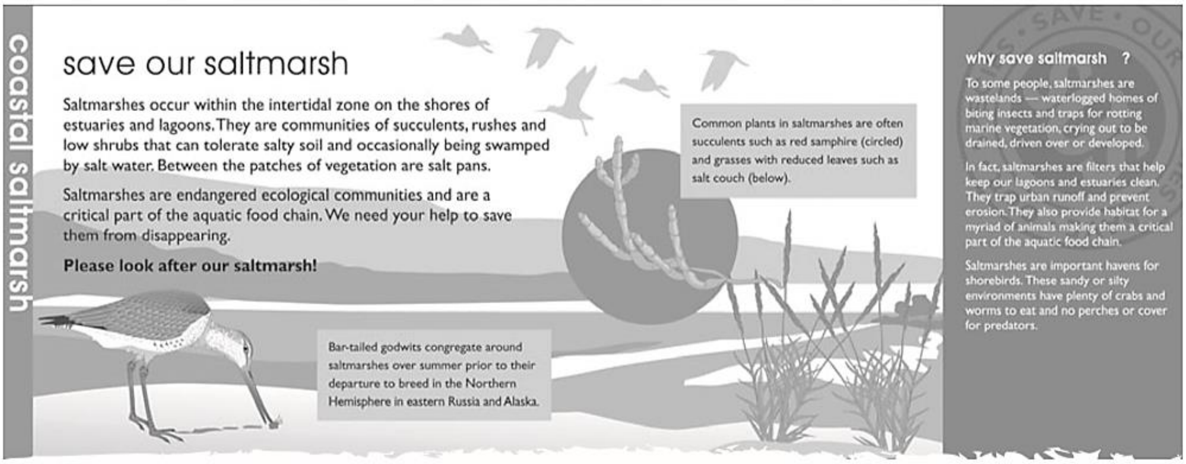

Figure 5: Saltmarsh educational signage at Koona Bay, Lake Illawarra (DECC 2008)

An example of a project which utilised passive remediation measures, including vehicle restriction and educational signage, is the Careel Bay saltmarsh rehabilitation project (Dalby-Ball & Olson 2012). Careel Bay is part of the lower Hawkesbury River estuary, on the central coast of NSW. Saltmarsh condition at this location prior to rehabilitation varied from highly disturbed to excellent (Dalby-Ball & Olson 2012). The project implemented measures to assist natural regeneration in an area damaged by mountain bikes, trampling and dumping of garden material (Dalby-Ball & Olson 2012). The project utilised passive rehabilitation techniques such as; fencing to limit access, removal of dumped garden material, removal of bike jumps, maintenance of nearby alternative jumps, installation of picture based educational signs and provision of information and education to schools, residents and the local newspaper (Dalby-Ball & Olson 2012). The outcome of the rehabilitation project has been a visible increase in cover of *Sarcocornia quniqueflora* in rehabilitated areas, decreased access and heightened community awareness of the importance of saltmarsh environments (Dalby-Ball & Olson 2012).

2.4.4 *Active rehabilitation*

Increased awareness of the importance of saltmarsh in Australia has led to an emergence of active rehabilitation efforts (Streever 1997; Laegdsgaard 2006). One of the most well documented forms of active saltmarsh rehabilitation in Australia is tidal reinstatement (Streever & Genders 1997; Howe et al. 2010; Haines 2013). This involves reversing previous works and changes to hydrology, in order to restore tidal inundation and thus provide suitable environmental conditions for saltmarsh re-establishment (Laegdsgaard et al. 2009; Haines 2013). Several sites in Homebush Bay, Sydney have been reverted from parkland to saltmarsh by restoring tidal inundation (Burchett et al. 1999b). Areas of Kooragang Island on the Hunter River estuary have been reverted from pastureland to saltmarsh, which has facilitated the return of migratory bird species (Russel et al. 2012). Weed removal is another form of active saltmarsh rehabilitation. Removal of *Juncus acutus* has become a focus for management in many parts of NSW, but is proving particularly difficult to eradicate (Laegdsgaard 2006; Paul & Young 2006). Common methods of control include chemical application and physical removal where feasible (Dixon 2006). Other measures most applicable to the rehabilitation of vehicle damaged saltmarsh are outlined below.

Sediment profile restructuring

Sediment profile restructuring involves reinstating the elevation suitable for saltmarsh, by filling eroded patches in the marsh surface (Green et al. 2009). Where the marsh surface needs reshaping, it is important to consider that saltmarsh species can be sensitive to a few centimetres change in elevation and tidal inundation (Laegdsgaard 2006). Green et al. (2009) monitored changes in vegetation on sub-tropical saltmarsh in response to sediment profile restructuring at Tweed Heads, northern NSW. This area had been impacted by sand mining, rubbish dumping, weed encroachment and more recently, off road vehicles (Green et al. 2009). Dominant species to be restored included *Sporobolus virginicus, Suaeda australis, Sarcocornia quinqueflora* and *Juncus kraussii.* To reinstate the appropriate elevation of the substrate, patches of remnant saltmarsh were connected through filling eroded patches with sand from an adjacent site (Green et al. 2009). Appropriate surface levels were determined using string across the sites at the height of the adjacent vegetated marsh surface (Green et al. 2009). To conserve any seed in the original surface soil, surface soils were removed to one side of the site for later replacement over the fill (Green et al. 2009). Half of the rehabilitation sites were subsequently planted with turves of *Suaeda australis,* whereas the other half received no planting (Green et al. 2009). After three years, significant colonisation occurred at all of the rehabilitation sites, whereas little change occurred at degraded controls (Green et al. 2009). There was strong seedling regeneration of several species, in particular *Sarcocornia quinqueflora* and *Suaeda australis.* This indicated a higher resilience and natural regeneration potential for these species (Green et al. 2009). In contrast, *Sporobolus virginicus* established only from vegetative growth. *Sporobolus* *virginicus* is generally reliant on vegetative mechanisms for colonisation, whereas *Sarcocornia quinqueflora* and *Suaeda australis* tend to be seed colonisers (Green et al. 2009). This study suggested that sediment profile restructuring alone may not be sufficient for less vagile species in isolated patches (Green et al. 2009). Similarly, Burchett et al. (1999a), conducted saltmarsh rehabilitation trials at Sydney Olympic Park and concluded that if suitable conditions of hydrology, salinity and tidal flushing are restored, common species including *Sarcocornia quinqueflora* and *Suaeda australis,* will colonise naturally and increase in cover significantly within three years.

When the marsh surface is relevelled to facilitate saltmarsh development, the suitability of transplanted topsoil/sediment is crucial. Elevated estuarine beds were created at Sydney Olympic Park to facilitate saltmarsh regeneration (Paul & Farran 2010). Although elevation was suitable for saltmarsh, poor topsoil that contained mainly rubble limited vegetation growth during the early stages of rehabilitation works (Paul & Farran 2010). Paul and Farran (2010) showed that if suitable substrate is not available, amelioration of topsoil/sediment through incorporation of mangrove mulch can significantly improve saltmarsh regeneration.

Use of seagrass wrack and mesh to facilitate natural regeneration

Seagrass wrack has the ability to shade soil, which can reduce salinity and increase moisture content and thus reduce physical stress (Chapman & Roberts 2004). In addition, wrack may provide nutrients to the soil which may be limiting in high shore, stressed habitats (Boyer & Zedler 1999; Chapman & Roberts 2004). Experimental addition of seagrass wrack to bare sediment adjacent to saltmarsh was undertaken at Tuggerah Lakes on the Central Coast of NSW (Chapman & Roberts 2004). On average, there was a rapid increase in the biomass of *Sarcocornia quinquflora* in areas where wrack was added. An increase in biomass of the dominant plant species, such as *S. quinqueflora,* may aid further regeneration of other saltmarsh species, by reducing physical stress (Chapman & Roberts 2004).

Mesh can be used in rehabilitation sites to assist natural regeneration, with the purpose of holding seeds in place as well as holding water, to create a moist micro-climate (Dalby-Ball & Olson 2012). Mesh can also be used to retain seagrass wrack (Dalby-Ball & Olson 2012). Coir mesh was used part of a rehabilitation project at Port Botany on the Penrhyn estuary, Sydney. Seeds were caught in the mesh, germinated and grew, but the surrounding area without mesh had very low levels of seedling germination (Dalby-Ball & Olson 2012). However, the use of open weave hessian at a nearby location on the Penrhyn estuary proved detrimental, because parts became loose and washed over seedlings during large tides (Sainty & Roberts 2012).

Replanting

Natural revegetation of saltmarsh may not always be possible, particularly in areas isolated from other saltmarsh habitats (Laegdsgaard 2006). In some cases it may be necessary to undertake replanting measures which can include cultivation from seedlings, transplantation of whole plants or transplantation of shoot cuttings (Burchett et al. 1999a). Transplantation may be from donor populations in nearby sites or from plants cultivated in greenhouses (Laegdsgaard 2006). Several species of saltmarsh plants including *Sporobolus virginicus, Sarcocornia quniqueflora, Suaeda australis, Wilsonia backhousei* and *Juncus krausii* can be successfully transplanted from greenhouses or donor populations (Pen et al. 1983; Burchett & Pulkownik 1996; Burchett et al. 1999a; Laegdsgaard 2002). However, plants that colonise spontaneously tend to grow better than transplanted individuals (Burchett & Pulkownik 1996). Furthermore, the best results from rehabilitation are generally achieved when the environment has been made suitable for natural colonisation (e.g. sediment profile restructuring) (Burchett et al. 1999a; Green et al. 2009). Replanting can play an important role in rehabilitating areas isolated from other established communities, because transport of seeds into these areas is unlikely (Burchett et al. 1999a). Replanting may also be useful in areas where increased biodiversity and regeneration of rare species is the desired outcome (Burchett et al. 1999a).

If replanting is used as a rehabilitation measure, a number of factors should be considered. If whole plants are to be transplanted from donor sites, impacts on the donor sites should be taken into account (Laegdsgaard 2006). The use of cuttings from donor sites may be an appropriate alternative to reduce damage to plant communities in these areas (Burchett et al. 1999a). Seasonal availability of seedlings and viability of the seed stock should be considered if cultivation of seedlings is the preferred rehabilitation method (Laegdsgaard 2006). Burchett et al. (1999a) found that the timing of replanting may impact the success of rehabilitation measures, with higher rates of survival and growth from cuttings taken in spring/summer than cuttings taken during autumn/winter.

3 Methods

3.1 Study Locations

Saltmarsh areas at Bermagui and Tomakin on the South Coast of NSW were used as study locations, to assess the impacts of vehicle passage on biotic and abiotic attributes of saltmarsh ecosystems (Figure 6). These locations were selected due to extensive evidence of vehicle disturbance and management concerns from South East Local Land Services (SE LLS). Tomakin (35°49' S, 150°11'E) is located approximately 250 km south of Sydney and Bermagui (36°25' S, 150°4' E) is located approximately 300 km south of Sydney. Both Bermagui and Tomakin experience a temperate, oceanic climate characteristic of the NSW South Coast, with annual mean maximum temperatures of 20.0 °C and 21.3 °C respectively. Uniform annual rainfall occurs in these areas with an average of 907.5 mm/year at Bermagui and 922.6 mm/year at Tomakin.

Figure 6: Bermagui and Tomakin study locations

3.1.2 *Location characteristics*

Bermagui

The Bermagui study area is located on a flood-tidal delta on the lower Bermagui River (OzCoasts 2015a). The Bermagui River is a mature, wave-dominated estuary, in a modified condition with twin training breakwaters (Roper et al. 2011). The river has an estuary area of 2 km^2 and the area of saltmarsh is estimated to be 14 ha (Roper et al. 2011). The extent of the study area is approximately 9.5 ha and elevations range between 0.10m and 1.65 m ASL (per obs. RTK GPS) (Figure 7).

The study area at Bermagui is located in the Bega Valley Shire Local Government Area (LGA) and is managed as a Conservation Area. Based on information from the Bermagui Historical Society (see Appendix I), the location has experienced long-term disturbance due to historical use as both a race course and an air-strip. During the early 1900's, a 1200m track was developed on the tidal delta flat for horse race meetings, and during the 1930's an air strip was established on the race course. Historical vehicle disturbance at the location has resulted in a network of well-defined tracks, developed from long-term usage from vehicles accessing the foreshore. It is likely that these tracks were generated by the use of remnant tracks from its past usage as a race course and air strip.

Figure 7: Bermagui study location in relation to the Bermagui River and township. Inset map depicts the extent of the study location. (Aerial imagery source: LPI 2014)

The level of disturbance from vehicles at this site is extensive (Figure 8). There are also high levels of erosion close to the water's edge, which may be partly associated with vehicle damage, vegetation decline and other hydrodynamic conditions (Figure 8, (e)). Accumulation of flood debris was evident in vehicle tracks, as a result of a large flooding event in June 2016 (Figure 8 (c) (d)). The area is a popular place for recreational activities such as fishing, walking and dog-walking. Although vehicle access has recently been restricted by fences erected by government managers, there is evidence that trail-bike and motorcycles regularly breach fencing (pers. obs.).

Figure 8: Vehicle damage at Bermagui

Clear zonation of vegetation communities in response to elevation was evident at this location, which is consistent with known patterns of saltmarsh zonation across tidal and elevation gradients previously documented by Clarke (1993) and Clarke and Hannon (1967). Dense patches of *Juncus kraussii* were dominant in higher marsh areas and often interspersed with the turf grass *Sporobolus virginicus* and the chenopod shrub *Suaeda australis* (Figure 9 (d)). At lower elevations, saltmarsh was dominated by *Sarcocornia quinqueflora,* interspersed with occasional patches of *Suaeda australis* (Figure 9 (b) (c)). At lower marsh elevations, *Avicennia marina* was mixed with *Sarcocornia quinqueflora*. At the lowest elevations, where tidal influence was higher, *Avicennia marina* was the dominant species. Patterns of marsh zonation used in this thesis were based on previous research by Clarke (1993), that was undertaken at six tidal inlets within Jervis Bay, NSW, Australia. Clarke (1993) documented the presence of all native plants at 1-m intervals along transects that were positioned perpendicular to the shoreline, within patches of saltmarsh within each inlet. Clarke (1993) found that the dominant native plants were configured in discreet zones that varied with elevation, and frequency and duration of tidal inundation. Specifically, across the six inlets it was found that *S. quinqueflora* regularly grew between 0.2-0.4 m ASL, whilst *J. kraussii* was generally restricted between 0.4 to 0.8 m ASL. The spatial distribution of *S. virginicus* was found by Clarke (1993) to be more varied and able to grow between 0.2-0.8 m ASL, and readily intermixed with S. *quinqueflora* and *J. kraussii* across the low and high marsh zones. For the purposes of my research I therefore stratified the marsh at Bermagui into two dominant zones: (1) the 'high marsh', dominated by *J. kraussii* and positioned at the highest elevations, and (2) the 'low' marsh, dominated by *S. quinqueflora* and bound on its seaward edge by mangrove (*Avicennia marina*) forests.

Other notable species at this location included threatened species *Wilsonia backhousei* and *Limonium australe. Limonium australe* is listed as vulnerable under the Commonwealth EPBC Act (1999) and *Wilsonia backhousei* is listed as vulnerable under the NSW TSC Act (1995). *Wilsonia backhousei* occurred in dense swathes close to the river bank at Bermagui (Figure 9 (a)). A comprehensive list of plant species that occur at this site was generated as part of the results section of this thesis, and is provided in Appendix II.

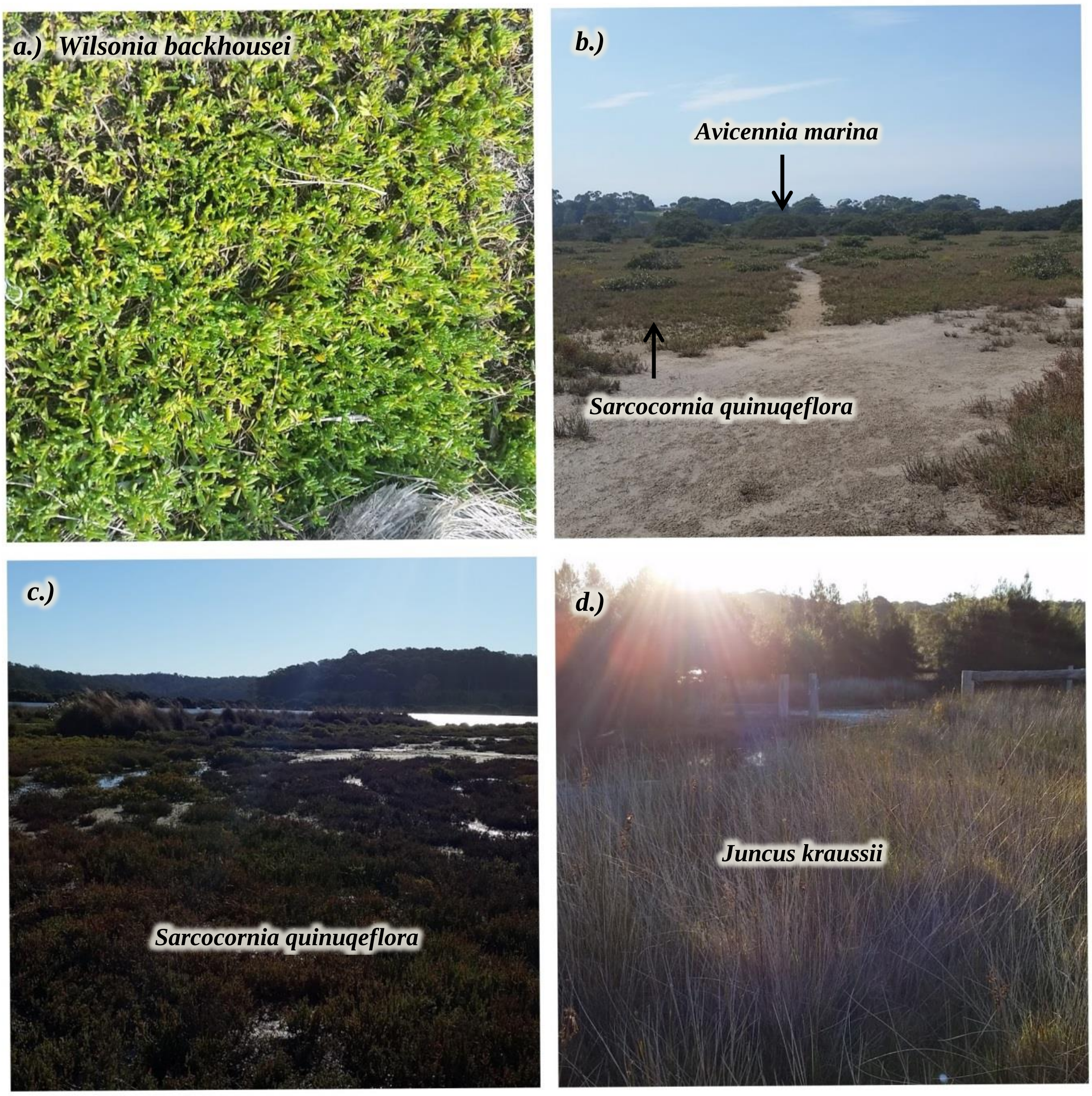

Figure 9: Dominant vegetation zones present at the Bermagui study location. a.), b.) and c.) depict species found in the lower marsh zone and d.) depicts the higher marsh zone.

Tomakin

The Tomakin study area is located on a flood-tidal delta on the lower Tomaga River, a mature river dominated estuary with a wave dominated delta (OzCoasts 2015b) (Figure 10). The condition of the estuary is largely unmodified, with no training walls altering entrance condition. The river has an estuary area of 1.35 km^2 and the area of saltmarsh within the estuary is estimated to be 46 ha (Roper et al. 2011). The extent of the study area is approximately 2.6 ha and elevations range between 0.30 to 1.15 m ASL (per obs. RTK GPS).

Figure 10: Tomakin study location in relation to the Tomaga River and Tomakin township. Inset map depicts the extent of the study location. (Aerial Imagery Source: LPI 2014)

The Tomakin study area is located on crown land in the Eurobodalla LGA. The access road to this site provides entry to nearby homes, and it is likely that local council will restrict general public access to the site in the future (K. Sampson 2016, pers. comm.). There is no direct access to the foreshore at this location, and as a result there is no evidence in the area of recreational activities such as walking or fishing. Despite this, extensive disturbance from 4WD vehicles is evident in the form of vehicle rutting in soil and denudation of vegetation (Figure 11). There is also evidence of other anthropogenic disturbances, such as fire and dumping of rubbish (Figure 11 (c) (e)).

Figure 11: Vehicle disturbance at the Tomakin study location

At Tomakin (in contrast to Bermagui), the saltmarsh vegetation was structured into a mosaic of single-species patches, with no clear elevational zonation. These patches were dominated by *Juncus kraussii,* which was occasionally mixed with invasive species *Juncus acutus* (Figure 12 (a)(b)(c)). Patches of mangrove (*Avicennia marina*) were abundant and interspersed between patches of typical saltmarsh plants *S. australis* and *S.quinqueflora* (Figure 12 (a)(b)(c)). A comprehensive list of all vegetation species at this location is included in Appendix III. Given the lack of clear elevational zonation of plant species across the marsh community at Tomakin, subsequent analysis simply compared the vegetation, seed bank and soil variables between impact (track) and control (no-track) sites.

Figure 12: Dominant vegetation patches at Tomakin including Juncus, Sarcocornia quniqueflora and Avicennia marina patches

3.2 Assessment of the soil seed bank and vegetation cover

3.2.1 Field sampling

Core sampling for seed bank analysis was conducted over a period of three days from the 13-15 May 2016. At each study location, 35 soil cores were randomly sampled from areas of the marsh where vehicle damage was evident (i.e. impact samples) and where vehicle damage was not evident (i.e. control samples). This equated to 70 cores per location and 140 cores in total. Vehicle damaged areas were defined as any area with evidence of vehicle disturbance, including any clearly defined tracks or vehicle rutting as shown in figures 8 and 11. Control cores were taken at least 2 m away from vehicle disturbance, to minimise any effects disturbance may have on directly adjacent saltmarsh. Soil cores were 5 cm deep and 8 cm in diameter, equating to a total soil volume of 251 cm^3 per soil core.

For each soil core, standing vegetation was surveyed within a 0.4 m x 0.6 m quadrat around each soil core (cores were taken in the centre of the quadrat). The quadrat size was chosen to fit inside a typical vehicle track/rut and for impact samples, the quadrat was positioned in the direction of the tracks, following the methods of Kelleway (2005). Percent cover by species was visually estimated within each quadrat and photos were taken to assist with species identification (Figure 13). Soil from cores was placed into sealed zip-lock bags in the field. Cores were transported in eskies to fridges at the University of Wollongong (34°25'S, 150°54'E) on the 16th of May and stored for 3 days before being processed and placed in the glasshouse.

Figure 13: Impact and control quadrats at Tomakin

3.2.2 Seedling emergence study

A seedling emergence study was undertaken to determine the identity and abundance of viable propagules within each soil sample, and compare between impact and control samples. This method has been demonstrated to be an effective technique for detecting the viable and germinable component of the seed bank (Brown 1992; Ter Heerdt et al. 1996). This was considered important for the objectives of this research, because the viable seeds are likely to contribute to regeneration of the community post disturbance (Brown 1992). Murphy (2014) conducted trials to measure the effectiveness of the seedling emergence study for evaluating estuarine seed banks. Considerable concurrence was found between number of seeds within soil examined by microscope and number of seedlings that germinated in the glasshouse, from soil taken at the same site (Murphy 2014). This indicated that the seedling emergence method was a sufficient method to assess the estuarine seed bank (Murphy 2014).

The seedling emergence study was undertaken at the Ecological Research Centre (ERC) at the University of Wollongong, following protocols outlined by Poiani and Johnson (1988), Gooden and French (2014) and Murphy (2014). Soil samples were spread across 17 cm x 11.5 cm propagation trays, over a base layer of 2 cm-thick coastal sand (Figure 14 (a) (b)). Seven control trays that contained sand only were interspersed between soil trays to detect contaminant seeds within the sand substrate and glasshouse. All trays were watered twice daily with tap water for 10 minutes via misters located 50 cm above trays. Tray positions were altered fortnightly to account for any microclimatic influences in the glasshouse on seedling germination. Seedlings were counted when large enough to accurately identify, and approximately every three to four weeks thereafter, over a period of 15 weeks. Prior research (Warr et al. 1993; Baldwin & Derico 1999; O'Donnell et al. 2014) has shown that approximately four months is an adequate time period to capture the majority of viable seeds within coastal seed banks. Murphy (2014) conducted a seedling emergence study in UOW’s ERC using soil from NSW saltmarsh sites and found that 90% of seedlings emerged within the first 8 weeks of the study. Therefore 15 weeks was considered a sufficient amount of time to capture the majority of viable seeds. When large enough, seedlings were removed from trays to prevent larger seedlings from supressing the growth of younger seedlings. Some seedlings were transferred to individual pots to grow to reproductive maturity to enable species identification (Figure 14 (d)).

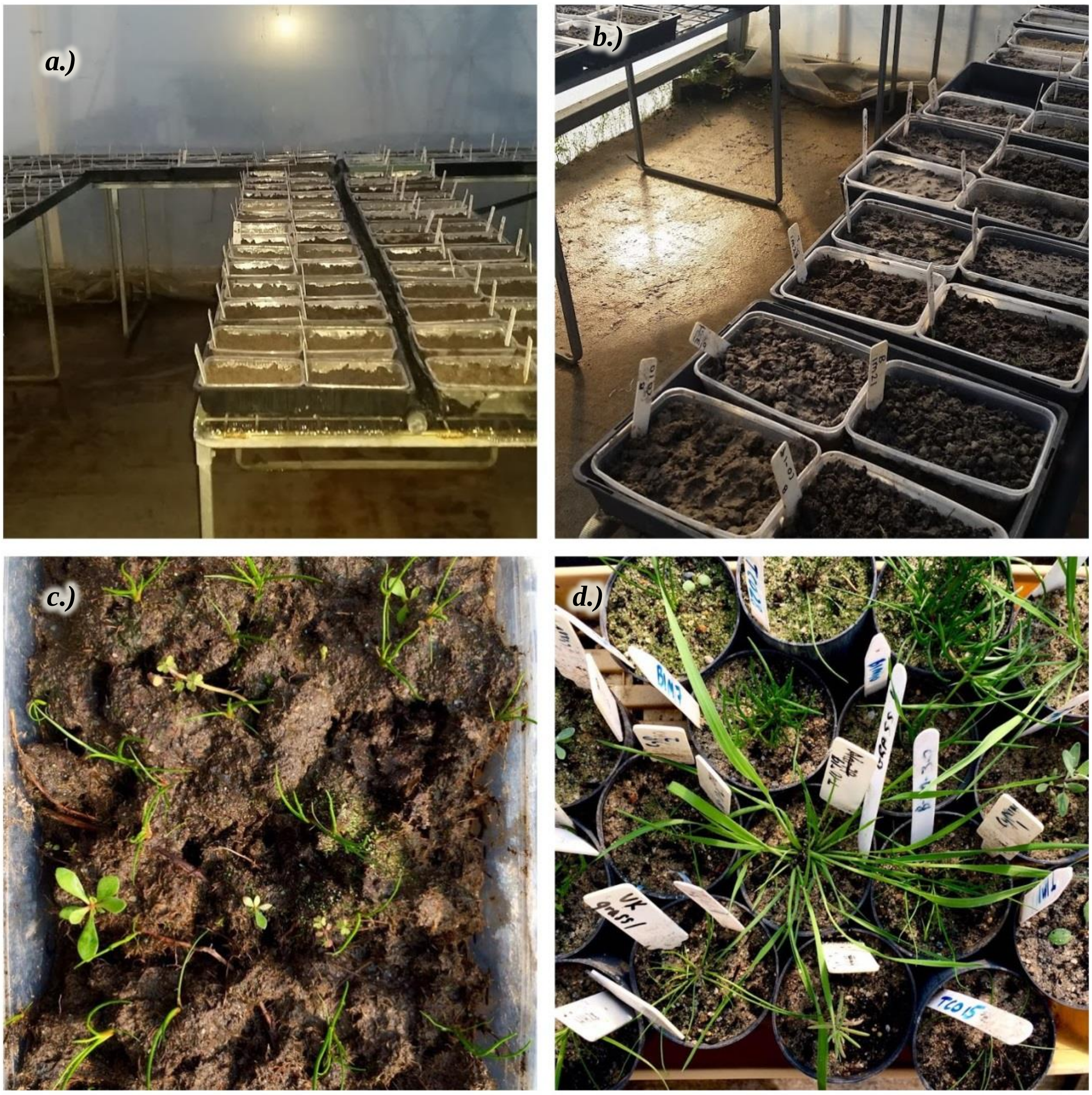

Figure 14:Trays and pots used in seedling emergence study at the University of Wollongong's ERC. (Photo credit: Ben Gooden)

3.2.3 Statistical analyses for vegetation and seed bank variables

Differences in seed bank and vegetation condition between impact and control saltmarsh at each location were assessed using two-factor mixed-effect analyses of variance (ANOVAs), using the statistical software package JMP 11. The dependent (i.e. response) variables were soil seed bank density (i.e. number of seedlings per core), soil seed bank richness (i.e. number of seedling species per core), vegetation abundance (i.e. percentage cover of vegetation per 50 cm × 70 cm plot) and vegetation richness (i.e. number of species per 0.4 m × 0.6 m plot). The independent (i.e. predictor) variables included location with two treatment levels (Bermagui and Tomakin, considered as a random effects) and vehicle damage with two treatment levels (vehicle-impact and control samples, considered as a fixed effect). The two-way ANOVA modelled the single effects of vehicle damage and location on each of the four response variables as well as the interactive effects. Data were square-root transformed where necessary to normalise distributions of residuals and improve homogeneity of variances. Normality was examined by inspecting residual-by-predicted plots of studentised residuals. An α significance threshold of 0.05 was used to determine the significance of all statistical tests conducted throughout this study. Post-hoc comparisons of means were performed using the Tukeys HSD test where interaction effects within ANOVAs were significant.

To assess the impacts of vehicle disturbance on the composition of species within the seed bank and above-ground vegetation, permutational multivariate analyses of variance (PERMANOVA) were undertaken, using the PRIMER 7 statistical package. Two-way PERMANOVAs were used to detect significant changes to species composition in response to both location and vehicle impact factors. A matrix of Bray-Curtis similarity indices was generated for each PERMANOVA, which ranked how similar the composition of each sample was from one another. The PERMANOVA then tested the null hypothesis that the Bray-Curtis similarity values were as close to all other samples regardless of the treatment category that they were assigned to. Compositional differences were found if the average similarity value was smaller between samples from the same treatment category (e.g. vehicle impacts samples) than an alternative treatment category (e.g. non-vehicle control samples). PERMANOVAs were performed using both species abundances (i.e. number of seedlings for the seed bank data and percentage species cover for the vegetation data) as well as species presence/absence data. This enabled me to assess the contribution of less common species to compositional change. For seedlings and vegetation cover, data for all species (i.e. native and weed species combined) and native species alone were analysed. Abundance and richness of invasive species alone were not analysed because occurrences were too low for the analyses to be successful. Where significant changes to composition were detected for the vehicle impact category or interaction effect, pairwise analyses of similarity were undertaken to determine the differences within each location. Where compositional differences were detected, similarity percentage (SIMPER) analysis was applied to identify the species' contributing to compositional change.

3.3 Assessment of environmental (abiotic) variables

3.3.1 Field sampling

To assess and compare soil characteristics between vehicle impacted and control saltmarsh, 40 additional soil cores were collected at each location (80 cores in total) on 28 June and 13 of July 2016. Cores were taken within vehicle tracks (impact) and adjacent undisturbed vegetation communities (control). For the 40 soils cores collected at each location, an uneven sampling regime was employed between impact and control sites. More control cores were taken to ensure variation in environmental conditions across vegetation types in control saltmarsh was sufficiently captured. Cores were 7 cm deep and 9 cm in diameter, equating to a total soil volume of 445.32 cm^3 per core.

At Bermagui, zonation of mangrove, higher saltmarsh and lower saltmarsh species was evident (outlined in section 3.3.1). Thus, vehicle impacted cores were categorised as either higher marsh impact or lower marsh impact, to account for any inherent differences in environmental conditions between the vegetation zones. At Bermagui, control cores were categorised into the following vegetation groups; higher saltmarsh species (dominated by *J. kraussi*) and lower saltmarsh species (dominated by *S. quinqueflora* with some *S. australis, W. backhousei* and *A. Marina* mixed throughout). Comparing environmental conditions in vehicle tracks to conditions within distinct vegetation communities was considered useful for inferring patterns of future vegetation regeneration. More specifically, inference could be made regarding the type of vegetation that was most likely to regenerate in damaged areas, by comparing impacted areas to vegetated areas with most similar environmental conditions. Figure 15 shows the location of soil cores used for analysis of soil properties, for each different category at Bermagui.

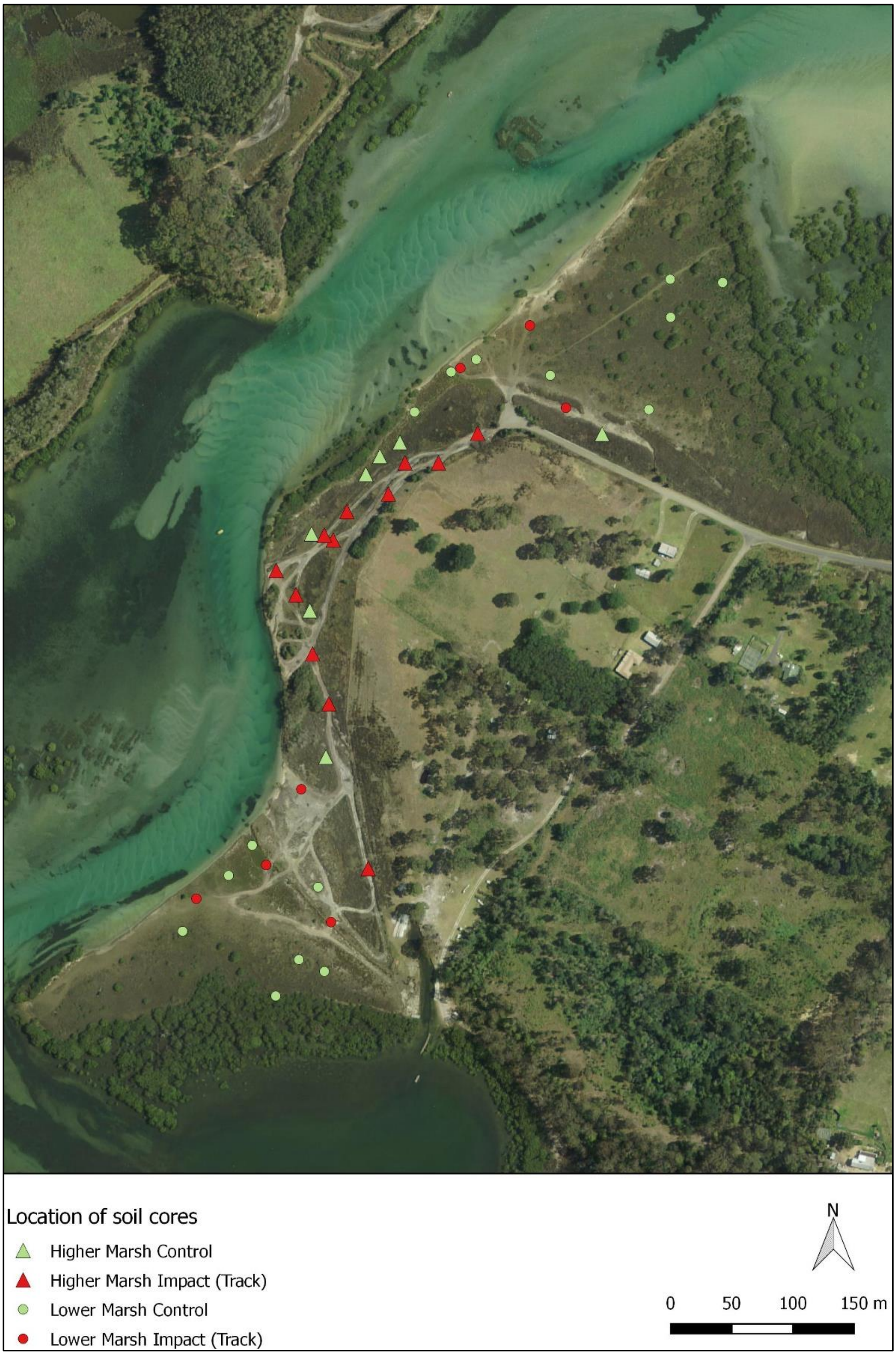

Figure 15: Location of soil cores used for analysis of soil properties, at Bermagui (Aerial Imagery: LPI 2014)

At Tomakin, vegetation communities were more spatially heterogeneous and clear zonation of higher and lower saltmarsh species was not evident (outlined in section 3.3.1). In areas impacted by vehicles, it was difficult to determine which vegetation type the track corresponded to, as zonation of dominant species was not evident. Therefore, vehicle impacted cores were classed as one group and not categorised based on surrounding vegetation zone. At Tomakin, control cores were categorised into the following vegetation groups; higher saltmarsh species (dominated by *J. kraussii* and *J. acutus*), lower saltmarsh species (typically dominated by *S. quinqueflora* and *S. australis*) and mangrove (dominated by *A. marina*). Figure 16 shows the location of soil cores used for analysis of soil properties, for each different category at Tomakin.

Figure 16: Location of soil cores used for analysis of soil properties, at Tomakin (Aerial Imagery: LPI 2014)

For each sample, the soil core location and elevation was measured using a Trimble Real Time Kinetic-Global Positioning System (RTK-GPS). In-situ vegetation cover by species was also surveyed for each core location, via the same method used for seed bank core collection. To characterise the chemical soil properties, salinity, electrical conductivity, pH and redox measurements were taken using a Toledo soil probe at each core location. These parameters were considered important because saltmarsh plant distribution and abundance is strongly associated with the chemical soil environment, which is influenced by factors such as soil oxygen level, inundation regime, nutrient availability, drainage and salinity of water and soil (Vince & Snow 1984; Bertness & Ellison 1987; Adam 1990). Specifically, salinity and electrical conductivity measurements were used to assess the relative influence of tidal and freshwater inputs, as well as levels of evaporation. Redox was used to indicate levels of soil aeration and waterlogging and pH was measured to determine if vehicle damage was associated with processes of soil acidification or alkalisation (Armstrong 1967; Adam 1990). Soil penetration resistance was measured using a hand-held penetrometer, to indicate levels of soil compaction. The average of 4 penetrometer measurements was recorded at each core location.

For each core, the soil was maintained inside the core, wrapped in plastic and taped. This was done to ensure the density of the soil was maintained for subsequent laboratory analysis. These were then placed into plastic sample bags and transported to a cool room at the University of Wollongong.

Spatial patterns in elevation and micro-topography across vehicle tracks were examined using RTK-GPS. RTK-GPS points were measured along a set of high resolution transects, that traversed the marsh and intersected the vehicle tracks at right angles. GPS points were recorded at approximately 0.5 m intervals, or when sharp changes in elevation occurred. Location of transects are shown in Figure 17.

Figure 17: Location of transects intersecting vehicle tracks, at a.) Bermagui and b.) Tomakin, used to spatially analyse variation in elevation and micro-topography in response to disturbance

3.3.2 Laboratory analysis

Bulk density and moisture content of each soil sample was determined following methods outlined by Howard et al. (2014b). Bulk density was assessed because it is considered a useful indicator for soil compaction (Nawaz et al. 2013). Soil moisture, which is negatively associated with bulk density (Raper 2005), was analysed because it has significant influence on plant growth and survival (Veihmeyer & Hendrickson 1950). . For each core, soil was subsampled from the surface of the core, and the base of the core equating to depths of 0 - 1.5 cm and 5.5 - 7 cm. Sub-sampling was undertaken to determine if trends in soil properties varied between surface and shallow sub-surface soil depths. Soil volumes of 2.65 cm^3 were subsampled using a 1.5 cm diameter syringe, to depths of 1.5 cm from the top and bottom of each core. Samples were weighed and then dried at 60°C in a laboratory oven at the University of Wollongong for 48 hours. Sub-samples were reweighed post drying to determine bulk density and moisture content. Moisture content was determined by calculating the difference in mass before and after oven drying. Bulk density was calculated using the following equations (Equations 1 and 2);

Equation (1): *Original volume sampled (cm^3) = [π*(radius of core barrel)^2*(depth of the sample, h*

Equation (2): $$Bulk\ Density\ (gcm^{-3}) = \frac{Mass\ of\ dry\ soil\ (g)}{Original\ volume\ sampled\ \ (cm^3)}$$

Dried soil samples used in analysis of bulk density and moisture content were subsequently used to determine % Loss on Ignition (LOI), following methods outlined by Howard et al. (2014a). LOI was used to indicate levels of soil organic matter, which is positively associated with overall soil quality (Schulte 1995). Approximately 3-5 g of each sub sample was dried overnight at 105°C to ensure all moisture had been removed from each sample. Samples were then weighed before being placed in a furnace at 375°C for approximately 16 hours. Samples were reweighed and % LOI was determined using the following equation (Equation 3);

Equation (3): $$\%\ LOI = \frac{Mass\ of\ soil\ after\ furnace}{Mass\ of\ soil\ before\ furnace}\ x\ 100$$

Grain size for each core sample was analysed using a Malvern Mastersizer laser particle scanner. Soil grain size was also considered an important factor contributing to overall soil quality, as the size and structure of soil particles are associated with retention of nutrients and soil organic matter (Kettler et al. 2001). Sub-sampling at 0-1.5 and 5.5-7 cm was also applied for grain size analysis. Soil samples were sieved prior to analysis to remove any large organic matter.

3.3.3 Statistical analysis of environmental (abiotic) variables

To compare the environmental conditions of vehicle impacted areas to control areas, a Principal Components Analysis (PCA) was undertaken using PRIMER 7. Environmental data included physical soil variables (bulk density, moisture content, loss on ignition and penetration resistance), chemical soil variables (salinity, electrical conductivity, redox, pH) and elevation. Prior to analysis, all variables were normalised and Euclidean distance indices were generated for each sample. Analysis was undertaken separately for each location. Multivariate analysis was undertaken using PERMANOVA, to determine if differences identified by the PCA were significant.

To determine the difference between impact and control saltmarsh for each specific environmental variable, 2-way ANOVA's were performed in JMP, via the same method applied to seed bank and vegetation variables (section 3.6.1). Independent (i.e. predictor) variables included location with two treatment levels (Bermagui and Tomakin, considered as a random effect) and vehicle damage with two treatment levels (impact and control samples, considered as a fixed effect). Tukey's HSD tests were performed where significant interaction effects were detected, to identify where trends differed within the location treatment.

Environmental data at Bermagui were analysed further, to determine if the impacts of vehicle disturbance varied between high and low saltmarsh zones. 2 way ANOVAS were performed using Bermagui data only, as per prior analyses. Independent (i.e. predictor) variables included marsh zone with two treatment levels (high marsh and low marsh, considered as a random effect) and vehicle damage with two treatment levels (impact and control samples, considered as a fixed effect). The two-way ANOVA modelled the single effects of vehicle damage and marsh zone on each of the four response variables as well as the interactive effects. Tukey's HSD tests were performed where significant interaction effects were detected, to identify where trends differed within the marsh zone treatment.

3.3.4 GIS analysis

Aerial photographic interpretation (API) was undertaken for each study location, to assess the spatial extent of vehicle damage. Major vegetation communities (outlined in section 3.1.2) and vehicle damaged areas at each location, were digitised in Arc Map 10.2. Vegetation polygons were digitised using the NSW Government's Lands and Property Information (LPI) 2014 ortho-rectified aerial imagery. Location of digitised vegetation and vehicle tracks were validated via on-site reconnaissance. Aerial imagery used for both Bermagui and Tomakin had a spatial resolution of 50 cm, which permitted accurate distinctions between major vegetation communities and vehicle tracks. These ground cover categories were used to derive statistics for subsequent hydrologic modelling.

Micro-topography of the marsh surface in response to vehicle damage was modelled, by importing RTK-GPS measurements to excel. The RTK GPS measurements corresponded to fine scale cross-sections taken across vehicle tracks, as shown in figure 17. Elevations were plotted against distance, to generate fine-scale micro-topographical transects across vehicle tracks.

Hydrology of the marsh surface was modelled for both study locations using Geographic Information Systems (GIS), to determine if vehicle tracks were associated with particular hydrological conditions. This process employed 1 m resolution Digital Elevation Models (DEMs) provided by LPI. DEMs were generated from 2013 LiDAR data at Bermagui and 2011 LiDAR data at Tomakin. Both datasets had a vertical accuracy of ± 0.3 m (LPI 2013). Although LiDAR data was considered to have a lower accuracy than RTK GPS (± 0.04 m) (Montane & Torres 2006), it was considered an effective means to evaluate micro-topographical trends (and thus hydrological trends) across the entire marsh at both study locations. Transects taken using RTK GPS were compared to corresponding DEM values, which revealed that although the DEM was not as effective at detecting fine-scale topographical variation, it was still an effective tool for detecting overall topographical trends between impact and control saltmarsh (Appendix V).

The Hydrology toolset, in ArcMap's spatial analyst toolbox was used to map hydrological variables at each location. DEMs were pre-processed using the Fill tool, to remove small imperfections in the surface rasters (ESRI 2011). The flow direction tool was then applied, which generated a raster of flow direction from each cell to its steepest downslope neighbour (ESRI 2011). The flow accumulation tool was then used to generate a surface raster representing accumulated flow of each cell, by calculating the weight of all cells that flow into each downslope cell (ESRI 2011). Output cells with high values of flow accumulation are considered areas of concentrated flow and can be used to identify stream channels. Output cells with low values are considered local topographic highs (ESRI 2011). Flow accumulation was considered useful for this study because it defines the locations of water concentration after rainfall or tidal flows (Dahal et al. 2008). The flow accumulation raster was directly compared to digitized ground cover classes at each location, to examine the relationship between flow accumulation and vehicle disturbance, as well as the various vegetation zones across the marsh. The 'Zonal Statistics by Table' spatial analyst tool was used to generate flow accumulation statistics for each ground cover class. Key statistics derived for each class included; means, standard deviations and number of cells. This process did not produce raw data for each ground cover class, and thus the differences between each ground cover class could not be statistically analysed. However, standard errors for each class could be generated from derived statistics and therefore significant differences could be inferred by comparing means and standard errors.

Results

4.1 Impacts of vehicle disturbance on vegetation

4.1.1 Spatial extent of vehicle damage

Aerial photo interpretation (API) revealed that the extent of vehicle damage at Bermagui, in the form of denuded saltmarsh vegetation, was approximately 1.67 ha. This equated to approximately 7.5% of the total study area (including mangroves) and 12.2 % of total saltmarsh area at this location. The extent of vehicle damage at Tomakin was shown to be approximately 0.13 ha. This equated to approximately 5.0% of the total study area (including mangroves). The extent of vehicle damage in relation to total saltmarsh area could not be determined at Tomakin, because mangrove and saltmarsh species did not occur in distinct zones. The location of vehicle damage and dominant vegetation communities at Bermagui and Tomakin are depicted in Figures 18 and 19 respectively.

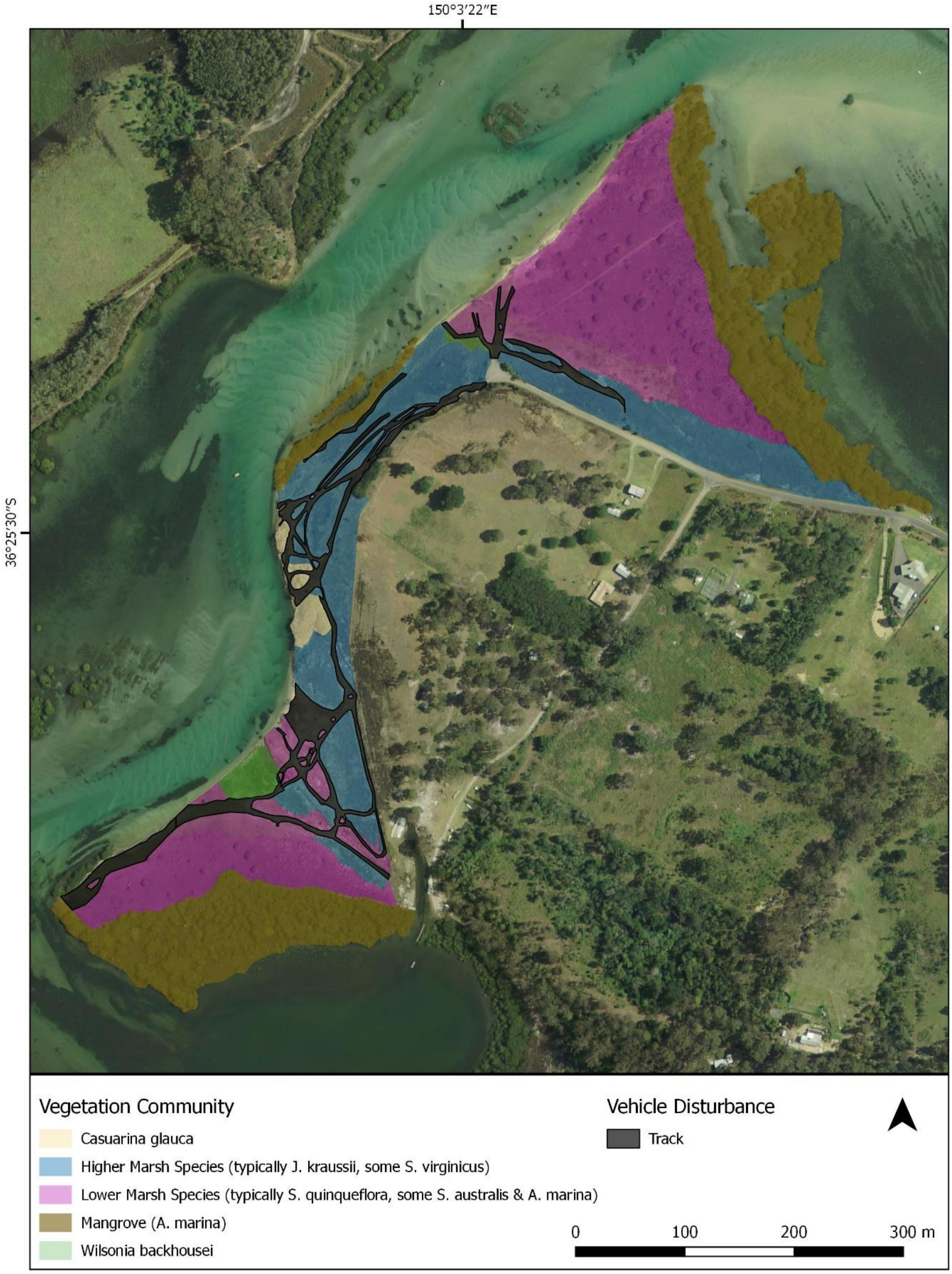

Figure 18: Extent of vehicle disturbance and dominant vegetation communities at the Bermagui study location. (Aerial imagery: LPI 2014)

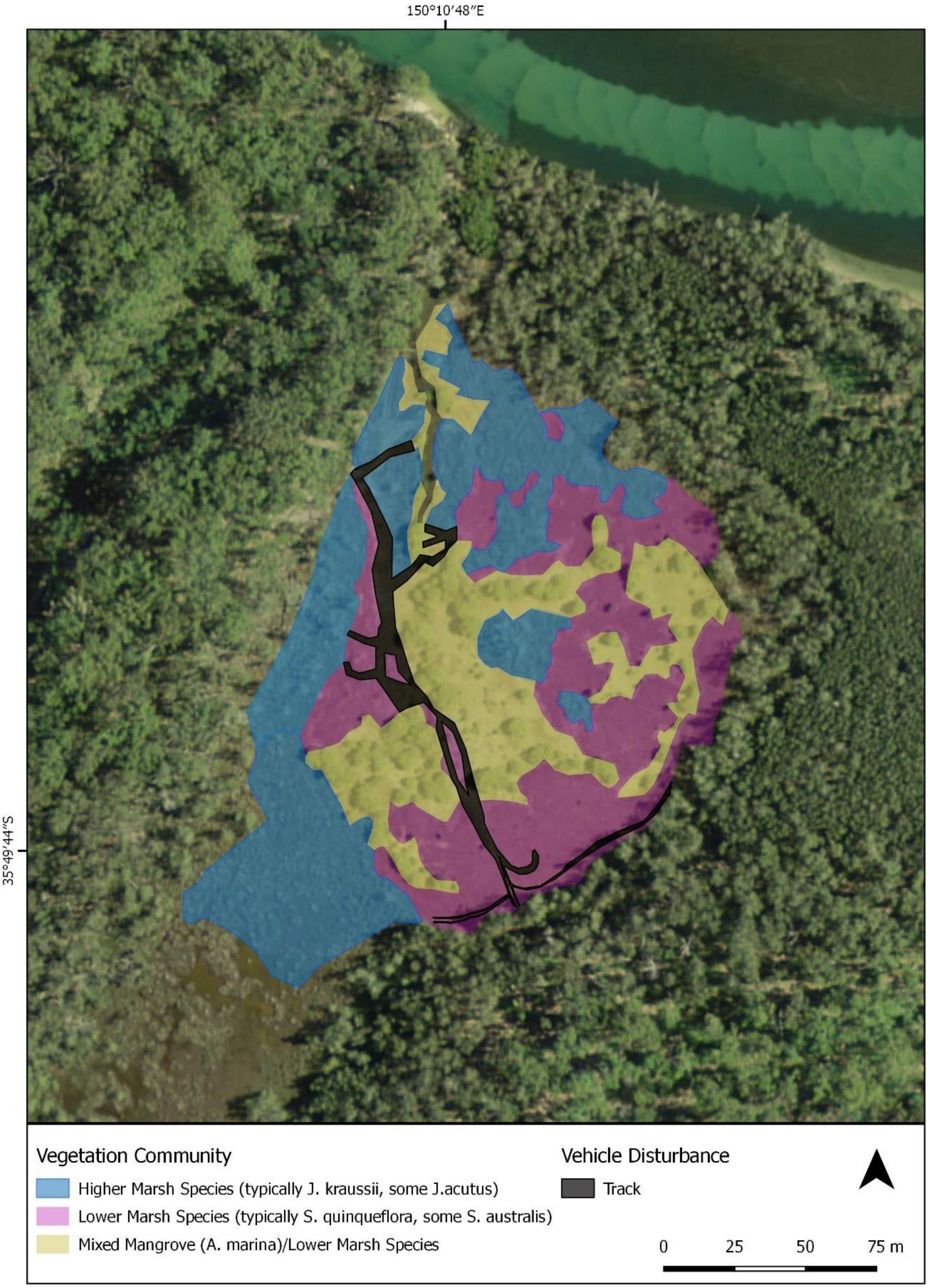

Figure 19: Extent of vehicle disturbance and dominant vegetation communities at the Tomakin study location. (Aerial imagery source: LPI 2014)

4.1.2 Vegetation cover and species richness

The percentage cover of standing vegetation differed significantly between vehicle-impacted and control quadrats, being 90 % lower on average in vehicle tracks at both locations (Table 7 and Figure 20 (a)). Species richness of the standing vegetation differed significantly between impact and control quadrats, being 2 ½ times lower in vehicle tracks (Table 7, Figure 20 (b)). When analysis was restricted to native species, similar results were obtained due to low abundances of invasive species at both locations (Table 7, Appendix VI).

*Table 7: Results from 2-way ANOVA comparing vegetation cover and species richness of cover (no. of species) between study locations and between impact and control areas. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions*

Response Variable Predictor variable	***df***	***SS***	***F***	***p***	***r^2***
Vegetation cover (%) (all species)					
Model	3	172896.59	162.63	**<0.0001**	0.78
Location	1	150.18	0.42	0.5162	
Vehicle Impact	1	171010.35	482.55	**<0.0001**	
Location x Vehicle Impact	13	1736.06	4.90	**0.0285**	
Error	6	221093.22			
Number of species/sample (all species) *					
Model	3	13.37	11.66	**<0.0001**	0.20
Location	1	0.19	0.50	0.4776	
Vehicle Impact	1	13.15	34.39	**<0.0001**	
Location x Vehicle Impact	13	0.023	0.07	0.7937	
Error	6	52.01			
Vegetation cover (%) (natives only)					
Model	3	169910.88	158.33	**<0.0001**	0.78
Location	1	271.61	0.76	0.3851	
Vehicle Impact	1	167533.21	468.35	**<0.0001**	
Location x Vehicle Impact	13	2106.06	5.89	**0.0166**	
Error	6	48648.06			
Number of species/sample (natives only) *					
Model	3	12.31	11.45	**<0.0001**	0.20
Location	1	0.01	0.03	0.8605	
Vehicle Impact	1	12.30	34.32	**<0.0001**	
Location x Vehicle Impact	13	0.00002	0.0001	0.9940	
Error	6	48.76			

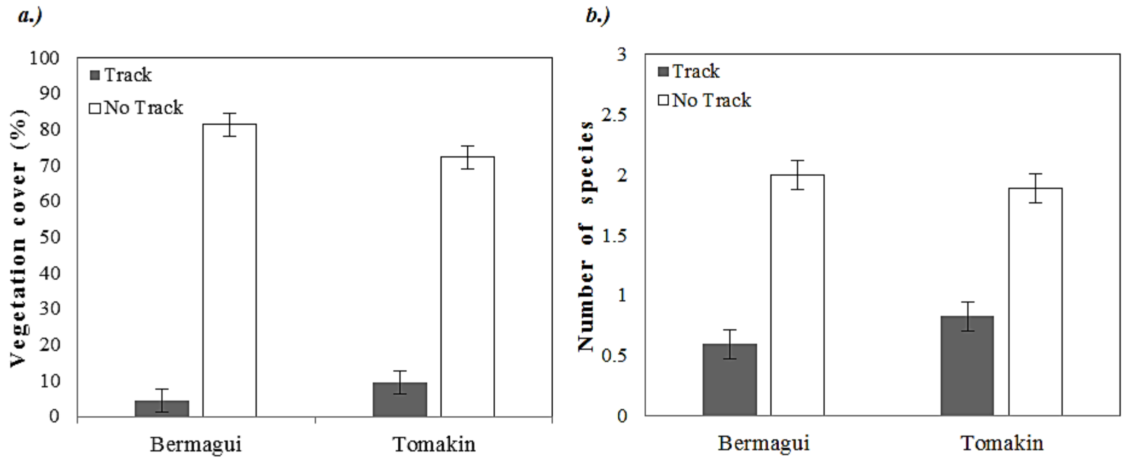

Figure 20: Mean (±SE) vegetation cover (a) and species richness (b) per quadrat, within impact (track) and control (no track) areas, at Bermagui and Tomakin

4.1.3 Vegetation community composition

The composition of standing vegetation (based on both species percentage cover abundance and presence/absence data) differed significantly between vehicle impact and control quadrats within each location. The 'Location' × 'Vehicle Impact' interaction term indicated that the species that contributed to compositional differences varied between locations (Table 8). Species driving compositional responses to vehicle tracks at Bermagui included *S. quinqueflora, J. kraussii, S. virginicus* and *W. backhousei*, with *S. quinqueflora* and *J. kraussii* contributing more than 50% collectively to community change (Table 8 and 9, Figure 21 (a)). At Tomakin, *S. quinqueflora*, *J. kraussii* and *A. marina* contributed up to 78% to compositional change (Table 8 and 9, Figure 21 (b)). All species at both locations were consistently less abundant within impact than control areas (Figure 21). However, *S. quinueflora,* was shown to be more abundant than any other species within vehicle tracks (Figure 21).

At Bermagui, it was shown that the presence/absence of vegetation species differed significantly between impact and control areas (Table 8). Despite being less abundant in tracks, *S. quinqueflora* was approximately 30% more likely to occur in tracks whereas *S. australis* was approximately 40% more likely to occur in tracks (Table 9). These species contributed most to compositional change in terms of presence/absence of species at Bermagui. *J.kraussii* and *S. virginicus* also contributed to change, with very low occurrences in impacted areas (Table 9). When analysis was restricted to native species, similar results were obtained due to low abundances of invasive species at both locations (Table 8, Appendix VI).

Table 8: PERMANOVA models of vegetation species composition for location and vehicle impact (using both abundance and presence/absence data). Bold indicates significant effects (or near significant effects). Pair-wise tests were performed where the interaction effect was significant (or close to), to determine effects within location

Response variable **Source of variation**	***df***	***SS***	***Psuedo – F***	***P (perm)***
Composition of species in vegetation cover (all species)				
Abundance				
Location	1	28889	8.7854	**0.001**
Vehicle Impact	1	67763	2.7966	0.496
Location x Vehicle Impact	1	24231	7.3688	**0.001**
Error	238	7.859×10^5		
Pairwise test 'Location vs Vehicle Impact' Within Bermagui			***t***	***p***
Track vs No Track			3.8855	**0.001**
Pairwise test 'Location vs Vehicle Impact' Within Tomakin				
Track vs No Track			3.4599	**0.001**
Composition of species in vegetation cover (all species)				
Presence/absence				
Location	1	24538	9.2629	**0.001**
Vehicle Impact	1	20875	0.64982	0.68
Location x Vehicle Impact	1	32124	12.126	**0.001**
Error	238	6.3314×10^5		
Pairwise test 'Location vs Vehicle Impact' Within Bermagui			***t***	***p***
Track vs No Track			3.78	**0.001**
Pairwise test 'Location vs Vehicle Impact' Within Tomakin				
Track vs No Track			1.5223	0.134

Table 9: SIMPER analysis identifying sources of compositional differences for vegetation species abundance between impact and control areas. Average dissimilarity values are average Bray-Curtis dissimilarity percentages.

Location	Species	Average abundance		Average dissimilarity	Dissimilarity/ SD	Contribution (%)	Cumulative contribution (%)
Abundance of all species							
		Control	**Impact**				
Bermagui							
	S. quinqueflora	15.48	5.32	25.62	0.82	27.82	27.82
	J. kraussii	22.08	0.20	21.69	0.72	23.55	51.36
	S. virginicus	14.49	0.00	14.11	0.56	15.32	66.68
	W. backhhousei	9.89	0.00	10.12	0.38	10.99	77.67
Tomakin							
	S. quinqueflora	28.15	10.19	34.82	1.06	40.68	40.68
	J. kraussii	21.03	1.07	22.50	0.79	26.29	66.98
	A. marina	6.75	2.19	14.43	0.60	16.86	83.8
Presence/absence of all species							
		Control	**Impact**				
Bermagui							
	S. australis	0.17	0.60	18.63	1.05	24.45	24.45
	S. quinqueflora	0.40	0.68	17.99	0.99	23.60	48.05
	J. kraussii	0.47	0.04	14.42	0.89	18.93	66.97
	S. virginicus	0.30	0.00	8.70	0.64	11.41	78.38

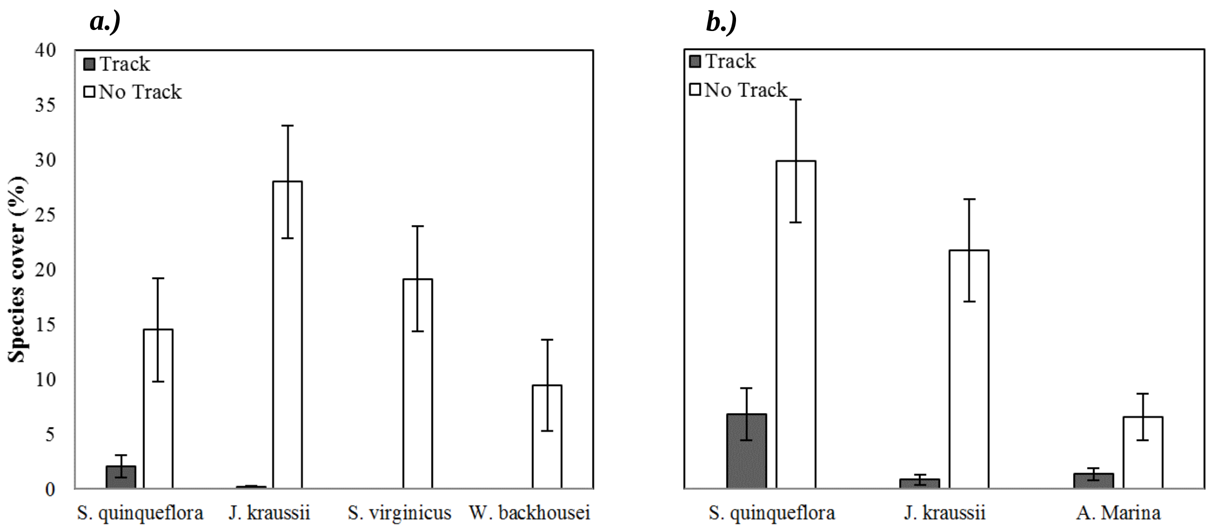

Figure 21: Abundance of species contributing most to compositional change in vegetation between impact and control samples for a) Bermagui and b) Tomakin

4.2 Impacts of vehicle disturbance on the soil seed bank

4.2.1 Seed density and species richness

A total of 1713 seedlings emerged from both impact and control soil samples at the two study locations. This equated to a mean seedling density across all location and impact treatments of approximately 12 seedlings per core sample. Rates of seedling emergence were similar between the two study locations, with approximately 55 % and 45 % derived from Tomakin and Bermagui, respectively. Overall, 25 vascular plant taxa were identified from the seed bank, which consisted of 15 native, 5 non-native (i.e. weed) and 5 that could be identified to family but not genus or species levels (of the 1,713 seedlings that were identified, only 0.05% could not be assigned to either a genus or species; Appendix IV). Native species dominated the seed bank, accounting for over 98% of emergent seedlings at both locations. The most abundant species' present in the seed bank at both locations were *Juncus kraussii* and *Samolus repens*, which comprised 56% and 32 % of all seedlings respectively.

Approximately 90% of seedlings emerged within the first 9 weeks of the study and 98% had emerged within 12 weeks, which suggests that 15 weeks was an adequate amount to sufficiently capture the majority of seeds within the soil. Figure 22 depicts the rate of seedling emergence for all germinants detected throughout the study.

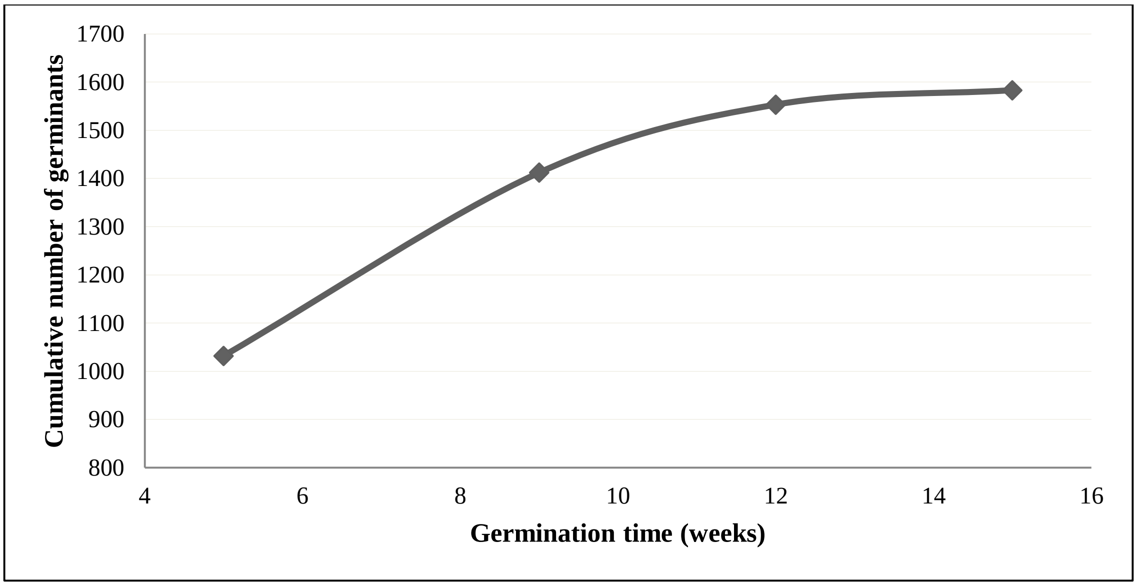

Figure 22: Cumulative number of germinants detected in the seedling emergence study for both study locations

There was a statistically significant negative effect of vehicle disturbance on seedling density (i.e. native and weed species combined), with five-times fewer seedlings germinating from impact soil samples compared to control samples. Seed density within vehicle impact samples was on average 4 seeds per core sample, whereas density in control areas was on average 20 seeds per sample (Table 10, Figure 23 (a)).

Species richness was also significantly lower in tracks, with on average twice as many species in control samples across both locations (Table 10, Figure 23 (b)). When weed species were removed from analyses it was still found that soil cores from vehicle damaged areas contained significantly fewer native seedlings and lower species richness in impact areas compared to control areas of saltmarsh (Table 10, Appendix VIII).

*Table 10: Results from 2-way ANOVA comparing seedling density and species richness (no. of species) between study locations and between impact and control areas. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions.*

Response Variable Predictor variable	*df*	*SS*	*F*	*p*	r^2
Seedling density (all species) *					
Model	3	175.58	12.80	**<0.0001**	0.22
Location	1	0.23	0.05	0.8232	
Vehicle Impact	1	174.36	38.13	**<0.0001**	
Location x Vehicle Impact	1	0.99	0.22	0.6425	
Error	136	621.86			
Number of species/sample (all					
species)*	3	13.37	11.65	<0.0001	0.20
Model	1	0.19	0.51	0.4776	
Location	1	13.15	34.39	**<0.0001**	
Vehicle Impact	1	0.03	0.069	0.7937	
Location x Vehicle Impact	136	52.01			
Error					
Seedling density (natives only)*					
Model	3	172.10	12.55	**<0.0001**	0.22
Location	1	0.56	0.11	0.7375	
Vehicle Impact	1	170.77	37.34	**<0.0001**	
Location x Vehicle Impact	1	0.81	0.18	0.6737	
Error	136	621.84			
Number of species/sample					
(natives only)*					
Model	3	12.31	11.4498	**<0.0001**	0.20
Location	1	0.01	0.0310	0.8605	
Vehicle Impact	1	12.30	34.3183	**<0.0001**	
Location x Vehicle Impact	1	0.000020	0.0001	0.9940	
Error	136	48.76			

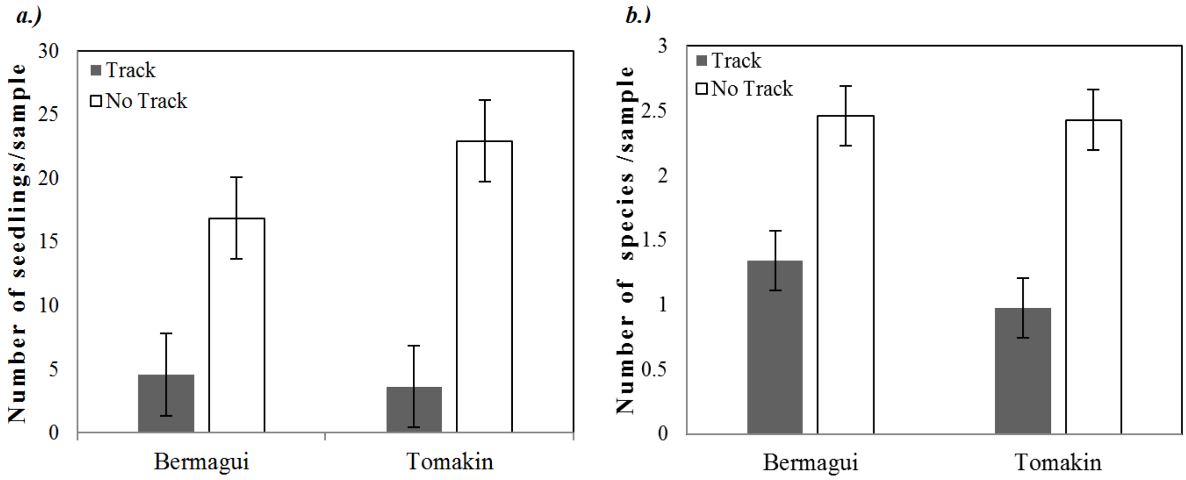

Figure 23: Mean (±SE) emergent seedling density (a) and species richness(b) in impact (track) and control (no track) areas, at Bermagui and Tomakin

4.2.2 Seed bank species composition

Community composition differed significantly between the two study locations, both when seedling density and presence/absence species data were incorporated into analyses (Table 11). However, compositions did not significantly differ between vehicle impact and control samples. This null result was an artefact of only including samples that contained at least one seedling in the analyses, given that Bray-Curtis similarity indices cannot be calculated between pairs of samples that contain zero values. This meant that, of the 140 original samples, 3 % of control samples and 63% of impact samples had to be excluded from the compositional analyses. Therefore, it is likely that impact samples did in fact contain different compositions of seedlings, but the analyses were not able to detect them. However, the interactive effect between 'Location' and 'Vehicle Impact' for abundance of native species exhibited a trend towards significance (i.e. P = 0.066), and thus a pair-wise test was used to explore this result further. SIMPER analysis revealed that the species contributing most (i.e. between 50 and 66%) to compositional differences between vehicle impact and control samples at both location was *Juncus kraussii* (Table 12). The density of *J. kraussii* seedlings was approximately four and two-times lower in impact than control areas at Bermagui and Tomakin, respectively (Table 12, Figure 24). At Bermagui, *Spergularia marina* also contributed to compositional differences but, conversely, was more abundant in the seed bank of impact samples. At Tomakin, *Samolus repens* contributed approximately 25% to compositional change, with vehicle-impacted areas containing significantly fewer seedlings on average than control areas (Table 12, Figure 24).

Table 11: PERMANOVA models of seedling species composition for location and vehicle impact (using both abundance and presence/absence data). Bold indicates significant effects (or near significant effects). Pair-wise tests were performed where the interaction effect was significant (or close to), to determine effects within location.

Response variable **Source of variation**	***df***	***SS***	***Psuedo – F***	***P (perm)***
Composition of species in seed bank (all species)				
Abundance				
Location	1	8155.4	2.716	**0.008**
Vehicle Impact	1	15079	3.2045	0.514
Location x Vehicle Impact	1	4705.4	1.5671	0.123
Error	108	324 290		
Composition of species in seed bank (all species)				
Presence/absence				
Location	1	13870	6.5582	**0.001**
Vehicle Impact	1	4739.8	2.0077	0.506
Location x Vehicle Impact	1	2360.8	1.1163	0.355
Error	108	228 400		
Composition of species in seed bank (natives only)				
Abundance				
Location	1	7862.1	2.9544	**0.02**
Vehicle Impact	1	16364	3.2085	0.493
Location x Vehicle Impact	1	5100.4	1.9166	**0.066**
Error	104	268 780		
Pairwise test 'Location vs Vehicle Impact' Within Bermagui			***t***	***p***
Track vs No Track			2.2048	**0.003**
Pairwise test 'Location vs Vehicle Impact' Within Tomakin				
Track vs No Track			1.7869	**0.013**
Composition of species in seed bank (natives only)				
Presence/absence				
Location	1	11947	7.9528	**0.001**
Vehicle Impact	1	5059.6	2.4312	0.503
Location x Vehicle Impact	1	2081.1	1.3853	0.255
Error	104	151 730		

Table 12: SIMPER analysis identifying sources of compositional differences for native species of seedling abundance between impact and control areas. Average dissimilarity values are average Bray-Curtis dissimilarity percentages.

Response Variable							
Location	**Species**	**Average abundance**		**Average dissimilarity**	**Dissimilarity / SD**	**Contribution (%)**	**Cumulative contribution (%)**
Abundance of native seedlings							
Bermagui		**Impact**	**Control**				
	J. kraussii	4.45	15.70	48.47	1.70	65.63	65.63
	S. marina	2.60	0.43	10.81	0.70	14.64	80.27
Tomakin							
	J. kraussii	4.17	9.77	35.95	1.47	49.51	49.51
	S. repens	0.08	12.00	18.19	0.69	25.05	74.56

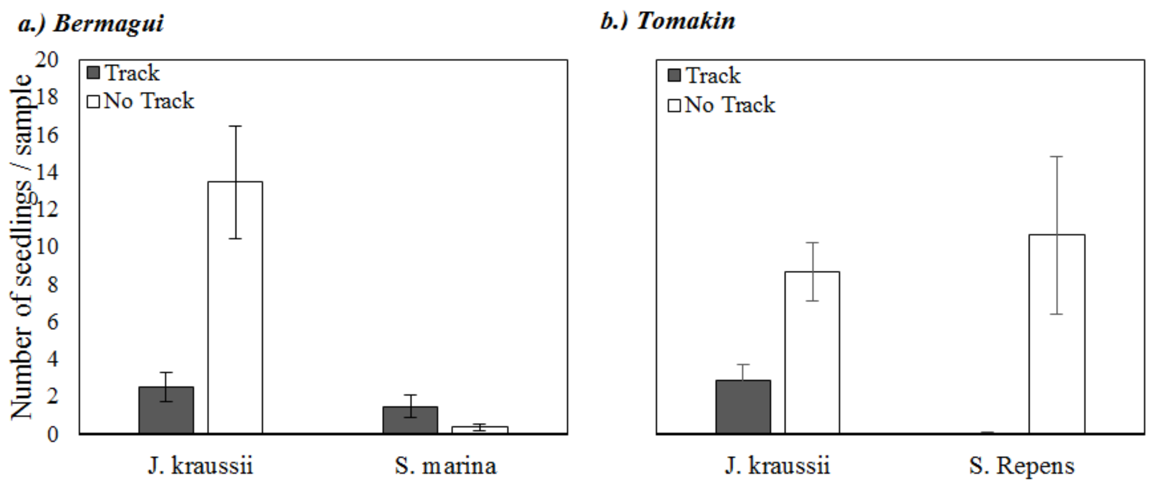

Figure 24: Density of seedlings for native species contributing most to compositional change in seedlings between impact and control samples for (a) Bermagui and (b) Tomakin

4.3 Impacts of vehicle disturbance on environmental (abiotic) conditions

At Bermagui, Principal Components Analysis (PCA) revealed that vehicle disturbance was associated with distinct changes to environmental conditions, with change largely driven by physical soil properties. The two principal components together explained 52.2 % of the total variation in the soil environment. Soil samples were clearly clustered within impact and control categories (Figure 25). These two impact and control clusters were almost entirely separated from one another along the PC1 axis, with impact cores clustered along the positive end of the axis and control cores clustered along the negative end of the axis (Figure 25). There was no separation between impact and control samples along the PC2 axis. It was confirmed with PERMANOVA that these apparent differences in soil properties between impact and control categories were statistically significant within both the high and low saltmarsh zones (Table 14). These differences in the soil environment were most strongly associated with soil bulk density and soil moisture content at both depths, as well as LOI for surface soil samples (0-1.5 cm depth), as indicated by the direction of eigenvectors within the PCA plot (Figure 25) and PCA loading values (Table 13).

The PCA analysis also showed differentiation of samples between the high and low marsh zones, generally along the PC2 axis (Figure 25). However, such differences only occurred in control samples, whilst the high and low marsh soil conditions began to converge on a similar soil state in vehicle-impacted areas (as indicated by the overlap in high and low marsh samples within the red cluster of vehicle impact samples; Figure 25). This indicates that the soil environment becomes homogenised across the marsh in the presence of vehicle damage.

Table 13: Loadings of the two principle component axes (PC1 and PC2) of the abiotic properties of High Marsh Control (HCO), Lower Marsh Control (LCO), High Marsh Impact (HIM) and Low Marsh Impact (LIM) samples at Bermagui

Variable	PC1	PC2
Bulk Density (g cm^{1}) (0-1.5 cm soil depth)	0.379	-0.278
Bulk Density (g cm^{1}) (5.5-7 cm soil depth)	0.324	-0.091
Moisture Content (%) (0-1.5 cm soil depth)	-0.375	0.203
Moisture Content (%) (5.5-7 cm soil depth)	-0.357	-0.034
Loss on Ignition (%) (0-1.5 cm soil depth)	-0.316	0.323
Loss on Ignition (%) (5.5-7 cm soil depth)	0.007	0.133
Grain size (microns) (0-1.5 cm soil depth)	0.193	-0.311
Grain size (microns) (5.5-7 cm soil depth)	0.251	-0.171
Penetration resistance (cm)	0.291	0.312
Salinity (ppt)	-0.238	-0.313
EC (µs/cm)	-0.224	-0.295
pH	0.214	0.334
Redox (mV)	-0.212	-0.347
Elevation (m AHD)	-0.036	0.332

Table 14: PERMANOVA model of abiotic variables for impact and dominant vegetation type (high/low). Bold indicates significant effects (or near significant effects). Pair-wise tests were performed where the interaction effect was significant

Response variable **Source of variation**	**Df**	**SS**	**Pseudo – F**	**P (perm)**
All environmental variables - Bermagui				
Vehicle Impact	1	132.12	132.12	0.508
Marsh zone (high/low marsh species)	1	58.498	58.498	**0.001**
Vehicle Impact x Marsh zone	1	30.488	30.488	**0.001**
	37	353.8	9.5623	
Pairwise test 'Position on marsh x Vehicle Impact'			***t***	***p***
Within High Marsh				
Track vs No Track			3.6296	**0.001**
Pairwise test 'Position on marsh x Vehicle Impact'				
Within Low Marsh				
Track vs No Track			1.9658	**0.001**

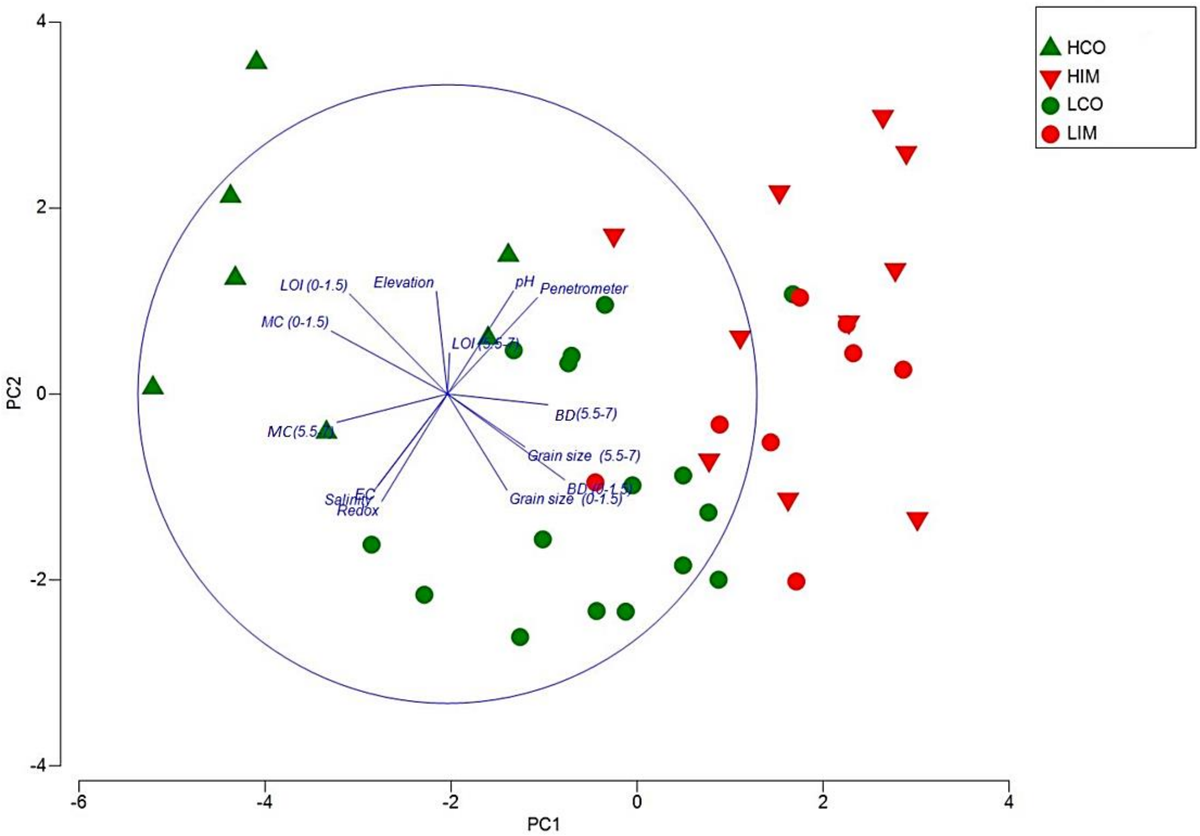

Figure 25: Ordination scatter plot of the two principle components (PC1 and PC2) to identify differences between the abiotic characteristics of High Marsh Control (HCO), Lower Marsh Control (LCO), Higher Marsh Impact (HIM) and Low Marsh Impact (LIM) samples at Bermagui. Impact samples are represented by red and controls by green.

At Tomakin, PCA revealed that vehicle disturbance was associated with changes to environmental conditions, but differences between impact and control areas were not as great as those found at Bermagui. The two principle components together explained 42.1% of the total variation in soil environment between the four vegetation categories: high and low marsh, mangrove and vehicle tracks (impact). Impact samples were in general clustered towards the positive end of the PC1 axis, which was most strongly associated with soil bulk density, moisture content and LOI at both soil depths analysed (Figure 26). Impact samples were spread fairly evenly across the PC2 axis but were more prevalent in the negative region (Figure 26). Overall there was considerable overlap between impact and all control categories. However, along the PC1 axis there was a particularly strong overlap between impact samples and mangrove samples. This indicates similarity in environmental conditions between impacted areas and areas with mangrove cover.

PERMANOVA showed that there were statistically significant differences in environmental conditions between impact and control samples, and pair-wise tests confirmed differences between impacted areas and each individual vegetation category (Table 16). Vehicle impacted samples were shown to be significantly different from all vegetation categories (Table 16). High marsh control and low marsh control samples were the only groups that did not differ significantly, indicating similarity in soil properties for these areas (Table 16). These differences in the soil environment were most strongly associated with soil bulk density, soil moisture content and LOI at both depths, as indicated by the direction of eigenvectors within the PCA plot (Figure 26) as well as PCA loading values (Table 15).

Table 15: Loadings of the two principle component axes (PC1 and PC2) for abiotic properties of Impact (IM), Higher Marsh Control (HCO), Lower Marsh Control (LCO) and Mangrove Control (MCO) at Tomakin.

Variable	**PC1**	**PC2**
Bulk Density (g cm^1) (0-1.5 cm soil depth)	0.372	-0.172
Bulk Density (g cm^1) (5.5-7 cm soil depth)	0.383	-0.168
Moisture Content (%) (0-1.5 cm soil depth)	-0.370	0.149
Moisture Content (%) (5.5-7 cm soil depth)	-0.413	0.177
Loss on Ignition (%) (0-1.5 cm soil depth)	-0.349	-0.081
Loss on Ignition (%) (5.5-7 cm soil depth)	-0.305	-0.086
Grain size (microns) (0-1.5 cm soil depth)	0.137	0.529
Grain size (microns) (5.5-7 cm soil depth)	0.126	0.397
Penetration resistance (cm)	0.069	0.384
Salinity (ppt)	0.012	0.336
EC (µs/cm)	-0.271	-0.099
pH	0.072	-0.200
Redox (mV)	0.106	-0.248
Elevation (m AHD)	0.250	0.256

Table 16: PERMANOVA model of abiotic variables for veg community (including impact samples). Bold indicates significant effects (or near significant effects). Pair-wise tests were performed where the interaction effect was significant

Response variable **Source of variation**	**Df**	**SS**	**Pseudo – F**	**P (perm)**
All environmental variables - Bermagui				
Marsh zone or Vehicle Impact	3	115.37	3.2148	
Error	36	430.63		
Pairwise test 'Marsh zone or Vehicle Impact'			***t***	***p***
High Marsh Control vs Low Marsh Control			1.3344	0.106
High Marsh Control vs Mangrove Control			2.4831	**0.001**
High Marsh Control vs Vehicle Impact			1.8954	**0.001**
Low Marsh Control vs Mangrove Control			1.7137	**0.007**
Mangrove Control vs Vehicle Impact			1.447	**0.019**

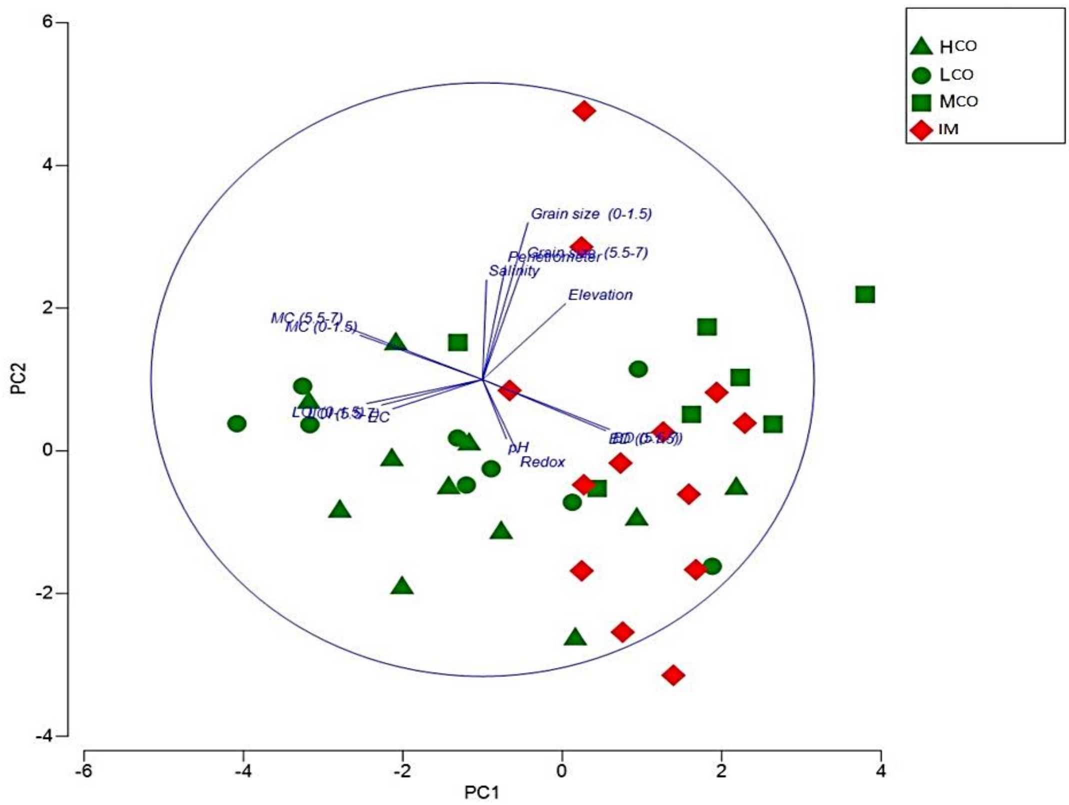

Figure 26: Ordination scatter plot of the two principle components (PC1 and PC2) used to identify differences between the abiotic characteristics of Vehicle Impact (IM), Higher Marsh Control (HCO), Lower Marsh Control (LCO) and Mangrove Control (MCO) samples at Tomakin. Impact samples are represented by red and control samples by green

4.3.1 *Impacts of vehicle disturbance on physical soil properties*

Although soil properties varied significantly between study locations, both locations exhibited very similar trends regarding the impact of vehicle disturbance on the soil. For all properties except subsurface grain size and penetration resistance, no interaction effect was found (Table 17). This indicated that for almost all soil properties measured, the same trends were prevalent across both locations.

For both surface (0-1.5 cm) and sub-surface (5.5-7 cm) samples, moisture content was significantly lower in impacted areas (Figure 27 (a) (b)). Soil from control areas had on average 25% more soil moisture at the surface, and 40% more soil moisture sub-surface. The difference between subsurface soil moisture for impacted and control samples was greater at Tomakin.

Bulk density of the soil at both depths was significantly higher in areas of vehicle impact (Figure 27 (c) (d)). The difference was greater at the surface; with bulk density 28% higher in impacted areas compared to control areas. For subsurface samples, bulk density was on average 17% higher in impacted areas.

LOI was significantly greater in control samples compared to areas of vehicle impact. This trend was stronger for soil at the surface (Figure 27 (e) (f)). At Tomakin, LOI from surface soil was approximately 3 times greater in control samples, whereas at Bermagui, LOI was twice as great for control samples. For sub-surface samples, LOI for both locations was just below 2 times higher in control areas compared to impacted areas.

Mean grain size was significantly higher in areas of vehicle impact for surface soil at both locations; with on average a 25% increase in grain size for impacted samples (Figure 28 (a)). For sub-surface samples, grain size was significantly higher at Bermagui, with a 33% increase in grain size for impacted samples compared to controls. At Tomakin, there was no significant difference between impact and control samples for grain size at sub-surface depths (Figure 28 (b)).

Soil compaction indicated by penetration resistance was significantly different between impacted and control samples at Bermagui, but this trend was not identified at Tomakin. At Bermagui, penetration resistance was more than twice as high in impacted areas compared to control areas (Figure 28 (c)).

*Table 17: Results from 2-way ANOVA comparing soil variables between study locations and between impact and control areas. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions. Table spans pages 68 and 69*

Response Variable Predictor variable	***df***	***SS***	***F***	***p***	***r²***
Soil Moisture Content (%) *					
Soil Depth = 0 – 1.5 cm					
Model	3	83.43	19.13	**<0.0001**	0.43
Location	1	61.86	42.56	**<0.0001**	
Vehicle Impact	1	12.03	8.28	**0.0052**	
Location x Vehicle Impact	1	1.20	0.83	0.3655	
Error	76	110.47			
Soil Moisture Content (%) *					
Soil Depth = 5.5 – 7cm					
Model	3	124.95	32.55	**<0.0001**	0.56
Location	1	68.01	53.15	**<0.0001**	
Vehicle Impact	1	31.08	24.29	**<0.0001**	
Location x Vehicle Impact	1	2.215	1.73	0.1923	
Error	76	97.25			
Bulk Density (g $cm^{3\,-1}$)					
Soil Depth = 0 – 1.5 cm					
Model	3	9.21	15.16	**<0.0001**	0.37
Location	1	6.05	29.87	**<0.0001**	
Vehicle Impact	1	1.98	9.76	**0.0025**	
Location x Vehicle Impact	1	0.09	0.46	0.5006	
Error	76	15.40			
Bulk Density (g $cm^{3\,-1}$)					
Soil Depth = 5.5 – 7cm					
Model	3	12.23	22.24	**<0.0001**	0.47
Location	1	7.46	40.74	**<0.0001**	
Vehicle Impact	1	2.35	12.82	**0.0006**	
Location x Vehicle Impact	1	0.17	0.92	0.3415	
Error	76	13.92			
Loss on Ignition (LOI) (%)*					
Soil Depth = 0 – 1.5 cm					
Model	3	48.78	8.26	**<0.0001**	0.24
Location	1	20.63	10.48	**0.0018**	
Vehicle Impact	1	14.70	7.46	**0.0078**	
Location x Vehicle Impact	1	3.98	3.98	0.1593	
Error	77	151.60			
Loss on Ignition (LOI) (%)*					
Soil Depth = 5.5 – 7cm					
Model	3	29.47	7.76	**<0.0001**	0.23
Location	1	19.05	15.05	**0.0002**	
Vehicle Impact	1	5.08	4.01	**0.0488**	
Location x Vehicle Impact	1	0.12	0.10	0.7576	
Error	77	97.47			

Mean grain size (microns)*					
Soil Depth = 0 – 1.5 cm					
Model	3	163.27	13.90	**<0.0001**	0.35
Location	1	135.46	34.59	**<0.0001**	
Vehicle Impact	1	16.37	4.18	**0.0444**	
Location x Vehicle Impact	1	4.17	1.07	0.3053	
Error	76	297.59			
Mean grain size (microns)*					
Soil Depth = 5.5 - 7 cm					
Model	3	166.85	18.62	**<0.0001**	0.42
Location	1	149.02	49.91	**<0.0001**	
Vehicle Impact	1	8.39	2.81	0.0979	
Location x Vehicle Impact	1	14.88	4.98	0.0285	
Error	76	226.93			
Penetration resistance (cm)					
Model	3	3505.19	60.24	**<0.0001**	0.56
Location	1	1791.00	92.34	**<0.0001**	
Vehicle Impact	1	990.64	51.08	**<0.0001**	
Location x Vehicle Impact	1	1110.24	57.24	**<0.0001**	
Error	157	3045.07			

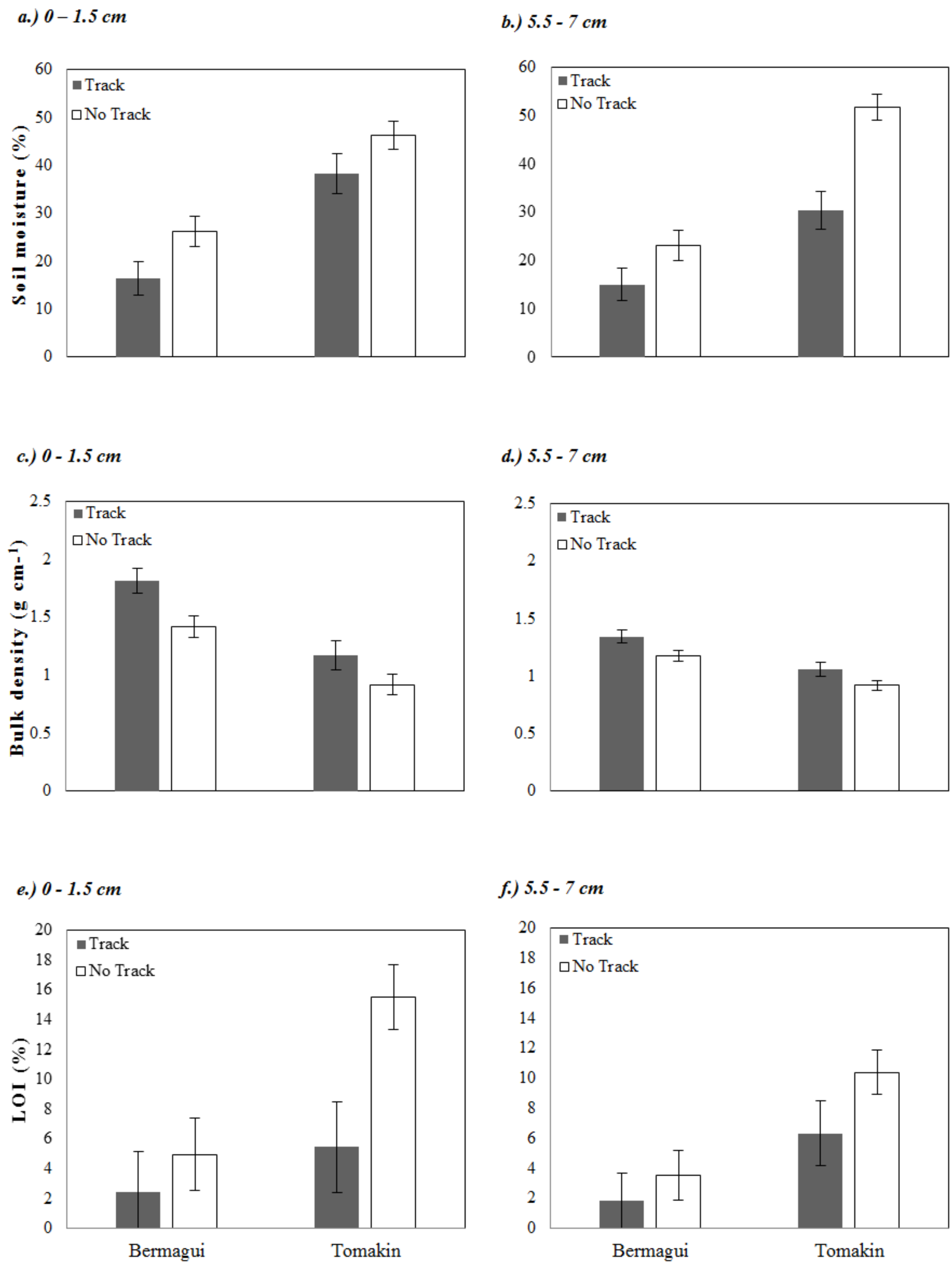

Figure 27: Mean (±SE) moisture content, bulk density and loss on ignition (LOI) within impacted (track) and control (no track) areas, for soil depths of 0-1.5 cm and 5.5 – 7 cm at Bermagui and Tomakin

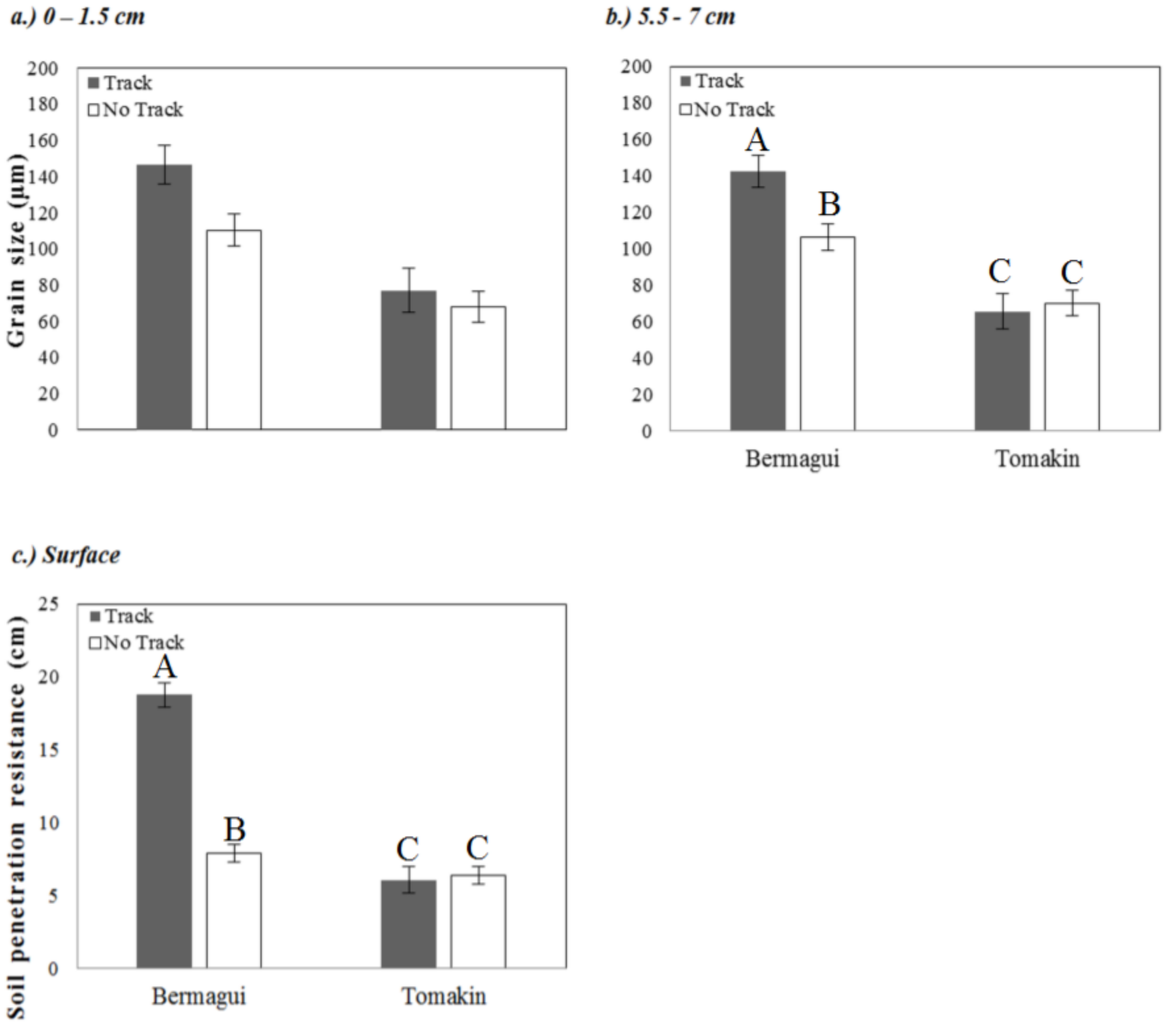

Figure 28: Mean (±SE) grain size and soil penetration resistance within impacted (track) and control (no track) areas, for soil depths of 0-1.5 cm and 5.5 – 7 cm at Bermagui and Tomakin. Letters denote significant differences demonstrated by Tukey's HSD test (only performed where significant interaction effect was found).

4.3.2 Impacts of vehicle disturbance on physical soil properties within high and low marsh zones at Bermagui

Analyses of soil variables for impact and control samples within different vegetation zones at Bermagui, revealed that for some properties, the effect of vehicle disturbance varied depending on marsh zone. These differences in the response to vehicle disturbance between marsh zone are indicated by the statistically significant interaction effects (Table 18). Overall, trends were similar to those detected between impact and control samples for both locations (Tomakin and Bermagui) (Figures 29 and 30). However, differences between the physical soil properties between impact and control areas were greater in the high marsh zone (Figures 29 and 30). Physical soil variables that were significantly different between impact and control samples in the high marsh zone, but not in the low marsh zone included soil moisture (at both depths), surface bulk density (0-1.5 cm deep), surface LOI, and subsurface grain size (5.5 – 7 cm deep) (Table 18, Figures 29 and 30).

*Table 18: Results from 2-way ANOVA comparing physical soil properties between marsh zone and between impact and control areas at Bermagui. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions. Table spans pages 72 and 73*

Response Variable Predictor variable	***df***	***SS***	***F***	***p***	***r^2***
Soil Moisture Content (%)					
Soil Depth = 0 – 1.5 cm					
Model	3	2260.76	26.52	**<0.0001**	0.68
Marsh zone (high/low)	1	651.10	22.91	**<0.0001**	
Vehicle Impact	1	1662.97	58.53	**0.0052**	
Marsh zone x Vehicle Impact	1	494.08	17.38	**0.0002**	
Error	40	3312.13			
Soil Moisture Content (%)					
Soil Depth = 5.5 – 7cm					
Model	3	985.72	11.94	0.1026	0.49
Marsh zone (high/low)	1	77.07	2.80	**<0.0001**	
Vehicle Impact	1	825.44	30.01	**<0.0001**	
Marsh zone x Vehicle Impact	1	254.08	9.24	**0.0043**	
Error	40	1017.91			
Bulk Density (g cm$^{3\ -1}$)					
Soil Depth = 0 – 1.5 cm					
Model	3	5.18	25.40	**<0.0001**	0.67
Marsh zone (high/low)	1	2.18	32.07	**<0.0001**	
Vehicle Impact	1	3.54	52.07	**<0.0001**	
Marsh zone x Vehicle Impact	1	0.79	11.57	**0.0016**	
Error	40	7.70			
Bulk Density (g cm$^{3\ -1}$)					
Soil Depth = 5.5 – 7cm					
Model	3	1.36	5.27	**<0.0040**	0.30
Marsh zone (high/low)	1	0.36	4.14	**0.0489**	
Vehicle Impact	1	1.16	13.49	**0.0008**	
Marsh zone x Vehicle Impact	1	0.15	1.80	0.1875	
Error	40	4.53			
Loss on Ignition (LOI) (%)*					
Soil Depth = 0 – 1.5 cm					
Model	3	17.00	13.63	**<0.0001**	0.53
Marsh zone (high/low)	1	13.26	31.92	**<0.001**	
Vehicle Impact	1	5.35	12.88	**0.0010**	
Marsh zone x Vehicle Impact	1	1.66	3.99	0.0531	
Error	40	15.37			
Loss on Ignition (LOI) (%)*					
Soil Depth = 5.5 – 7cm					
Model	3	0.80	0.52	0.5120	0.04
Marsh zone (high/low)	1	0.001	0.0018	0.8556	
Vehicle Impact	1	0.017	0.034	0.9661	
Marsh zone x Vehicle Impact	1	0.77	1.49	0.2301	
Error	40	19.20			

Mean grain size (microns)*					
Soil Depth = 0 – 1.5 cm					
Model	3	13.48	13.47	**<0.0001**	0.18
Marsh zone (high/low)	1	1.65	1.65	0.5964	
Vehicle Impact	1	34.92	34.92	**0.0121**	
Marsh zone x Vehicle Impact	1	9.54	9.54	0.1760	
Error	40	185.51			
Mean grain size (microns)*					
Soil Depth = 5.5 - 7 cm					
Model	3	47.51	4.76	**0.0066**	0.28
Marsh zone (high/low)	1	5.43	1.63	0.2094	
Vehicle Impact	1	34.14	10.26	**0.0028**	
Marsh zone x Vehicle Impact	1	17.43	5.24	**0.0278**	
Error	40				
Penetration resistance (cm)					
Model	3	20.80	6.69	**0.0010**	0.35
Marsh zone (high/low)	1	2.17	2.09	0.1568	
Vehicle Impact	1	14.57	14.05	**0.0006**	
Marsh zone x Vehicle Impact	1	0.90	0.90	0.3570	
Error	40	38.37			

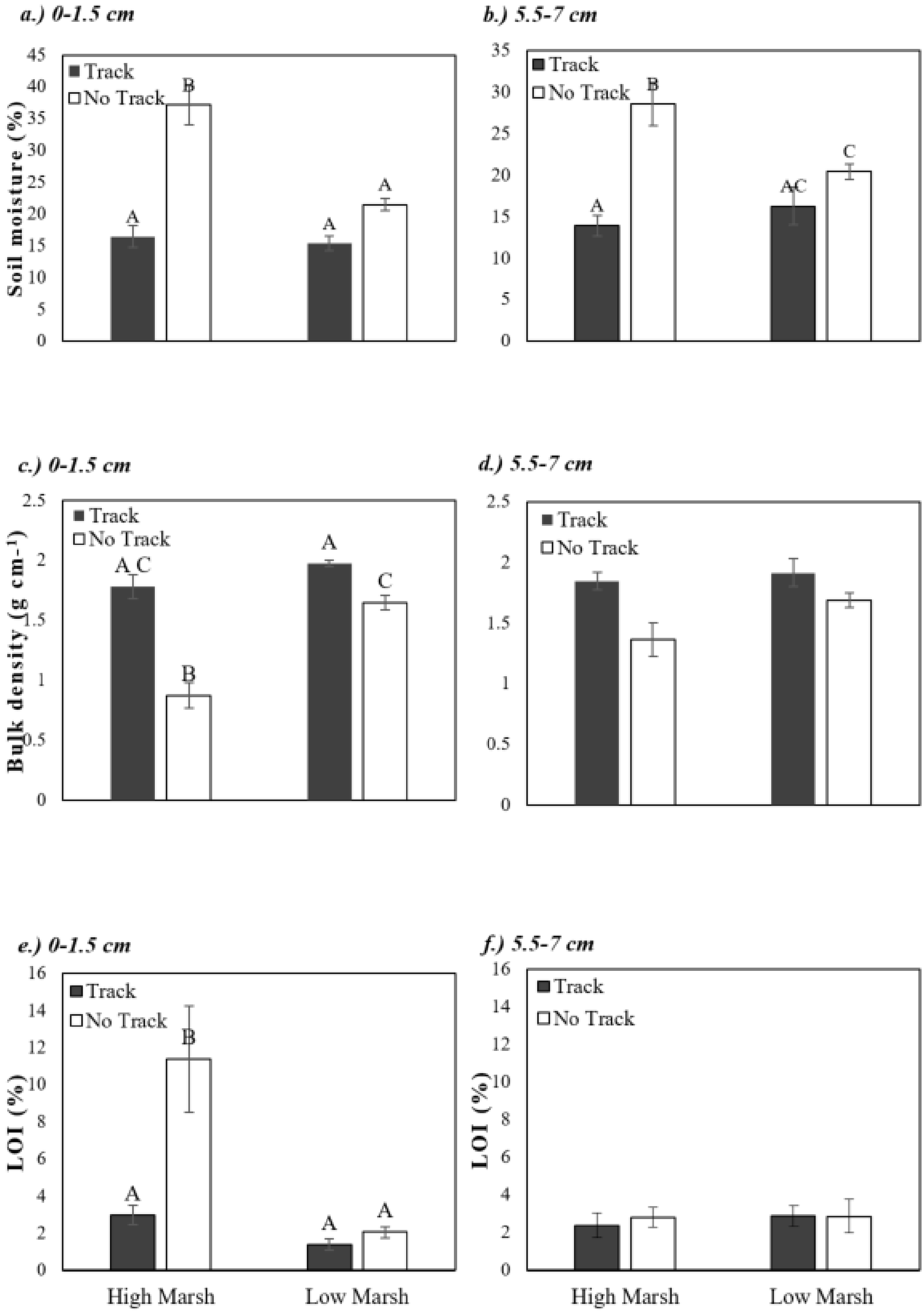

Figure 29: Mean (±SE) soil moisture, bulk density and LOI within impacted (track) and control (no track) areas, for soil depths of 0-1.5 cm and 5.5 – 7 cm within high and low marsh zones at Bermagui. Letters denote significant differences demonstrated by Tukey's HSD test (only where significant interaction effect were found).

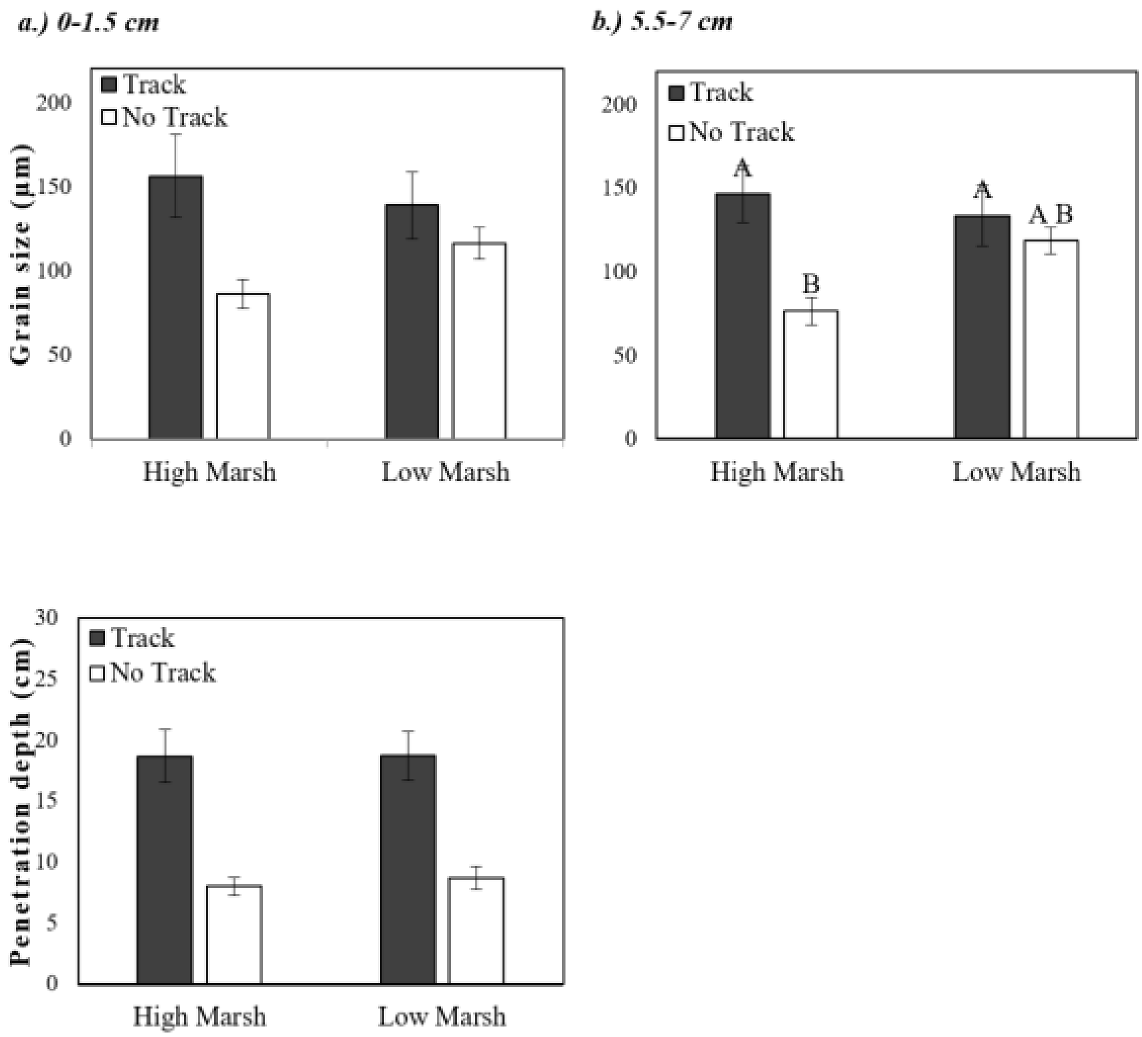

Figure 30: Mean (±SE) grain size and soil penetration resistance within impacted (track) and control (no track) areas, for soil depths of 0-1.5 cm and 5.5 – 7 cm within high and low marsh zones at Bermagui. Letters denote significant differences demonstrated by Tukey's HSD test (only where significant interaction effect was found)

4.3.3 Impacts of vehicle disturbance on chemical soil properties

Similar to soil properties, chemical soil properties varied significantly between locations. However, impacts of vehicle disturbance remained very similar for both locations (Table 19). Salinity was lower in areas of vehicle disturbance at both locations (Figure 31). This trend was not identified as significant ($p < 0.05$) but demonstrated a trend towards significance ($p = 0.0788$) (Table 19). A similar trend was found for electrical conductivity (EC), which was lower in impacted areas but not significantly (trend towards significance, $p = 0.1345$) (Table 19). Salinity was 12% lower and EC was 10% lower inside tracks for both locations. There was no significant difference in pH at both locations between impact and control areas (Table 19). Redox was found to be significantly lower in impacted areas and the difference was greater at Tomakin (Table 19, Figure 31). Redox was approximately 40% lower in tracks at Tomakin and 10% lower in tracks at Bermagui (Figure 31).

*Table 19: Results from 2-way ANOVA comparing chemical soil properties between study locations and between impact and control areas. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions.*

Response Variable Predictor variable	***df***	***SS***	***F***	***p***	***r^2***
Salinity (ppt) *					
Model	3	25.72	38.81	**<0.0001**	0.62
Location	1	23.25	105.27	**<0.0001**	
Vehicle Impact	1	0.70	3.1814	0.0788	
Location x Vehicle Impact	1	0.35	1.5891	0.2116	
Error	74	15.68			
Electrical Conductivity (mS/cm) *					
Model	3	38.53	40.09	**<0.0001**	0.63
Location	1	35.18	109.82	**<0.0001**	
Vehicle Impact	1	0.73	2.29	0.1345	
Location x Vehicle Impact	1	0.32	1.01	0.3189	
Error	74	22.74			
pH					
Model	3	0.01	0.64	0.5888	0.03
Location	1	0.003	0.53	0.4686	
Vehicle Impact	1	0.0004	0.06	0.8038	
Location x Vehicle Impact	1	0.0058	0.99	0.3242	
Error	74	0.43			
Redox (mV)					
Model	3	137.20	32.1995	**<0.0001**	0.58
Location	1	130.83	92.1097	**<0.0001**	
Vehicle Impact	1	16.01	11.2735	**0.0013**	
Location x Vehicle Impact	1	5.54	3.9033	0.0521	
Error	74	100.84			

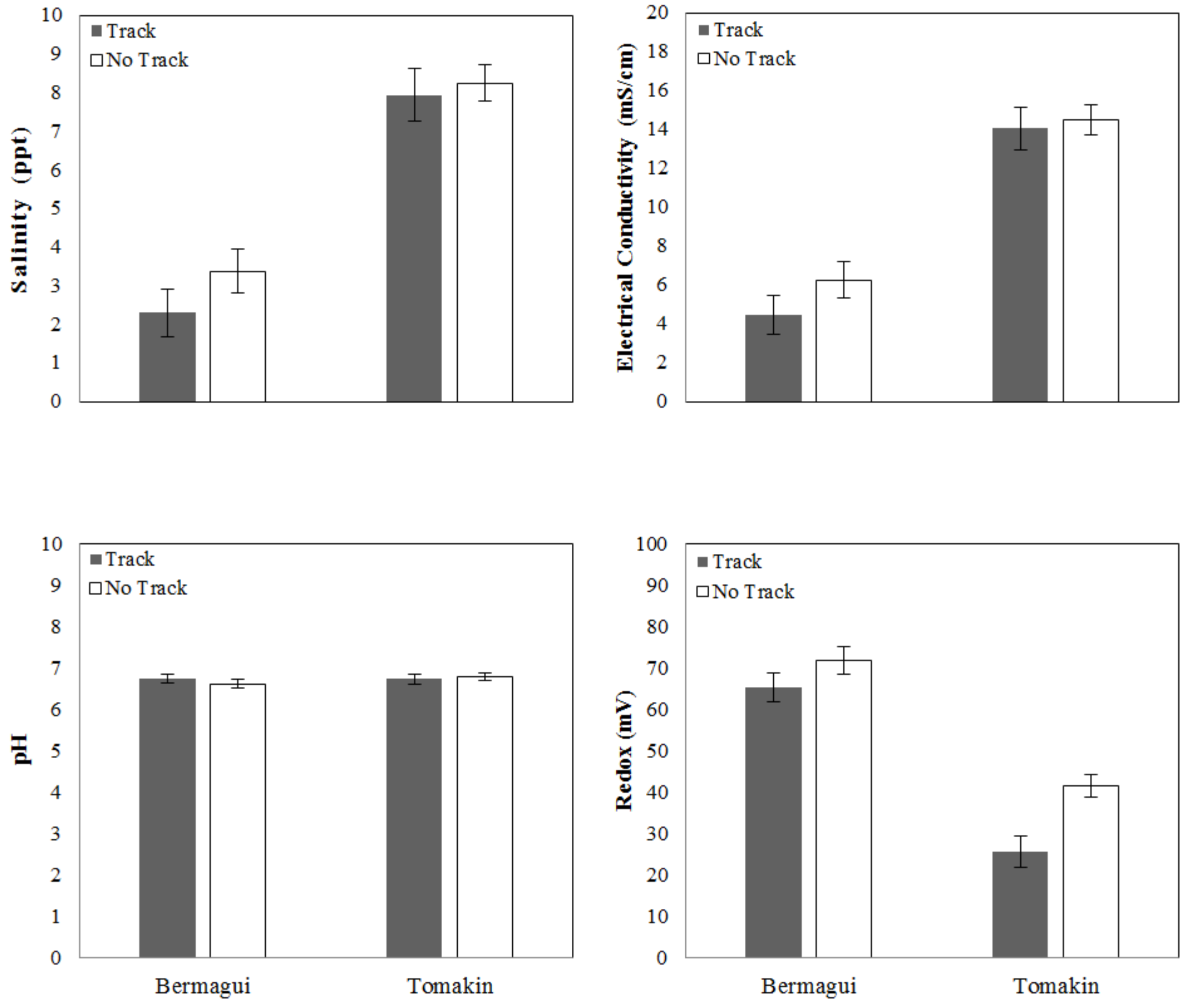

Figure 31: Mean (±SE) salinity, electrical conductivity, pH and redox within impacted (track) and control (no track) areas at Bermagui and Tomakin

4.3.4 Impacts of vehicle disturbance on chemical soil properties within high and low marsh at Bermagui

In contrast to physical soil properties, the effect of vehicle disturbance did not significantly differ between high marsh and low marsh zones at Bermagui (Table 20). Within each vegetation zone, impact samples had significantly lower levels of salinity and electrical conductivity (Figure 32), but did not differ significantly between high and low marsh zones. Redox and pH did not vary significantly differ in response to vehicle impact or marsh zone (Table 20, Figure 32).

*Table 20: Results from 2-way ANOVA comparing chemical soil variables between marsh zone (high/low) and between impact and control areas at Bermagui. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions*

Response Variable / Predictor variable	***df***	***SS***	***F***	***p***	***r^2***
Salinity (ppt)					
Model	3	20.82	6.68	**0.0010**	0.35
Marsh zone (high/low)	1	2.17	2.08	0.1568	
Vehicle Impact	1	14.57	14.05	**0.0006**	
Marsh zone x Vehicle Impact	1	0.90	0.87	0.3570	
Error	40	38.37			
Electrical Conductivity (mS/cm)					
Model	3	48.74	5.70	**0.0026**	0.32
Marsh zone (high/low)	1	3.99	1.40	0.24343	
Vehicle Impact	1	35.95	12.61	**0.0011**	
Marsh zone x Vehicle Impact	1	0.91	0.32	0.5746	
Error	40				
pH					
Model	3	0.007	1.10	0.3588	0.08
Marsh zone (high/low)	1	0.002	0.08	0.7801	
Vehicle Impact	1	0.053	2.52	0.1205	
Marsh zone x Vehicle Impact	1	0.014	0.66	0.4201	
Error	40				
Redox (mV)					
Model	3	230.07	1.18	0.3298	0.09
Marsh zone (high/low)	1	7.92	0.12	0.7287	
Vehicle Impact	1	176.02	2.71	0.1080	
Marsh zone x Vehicle Impact	1	36.32	0.56	0.4590	
Error	40				

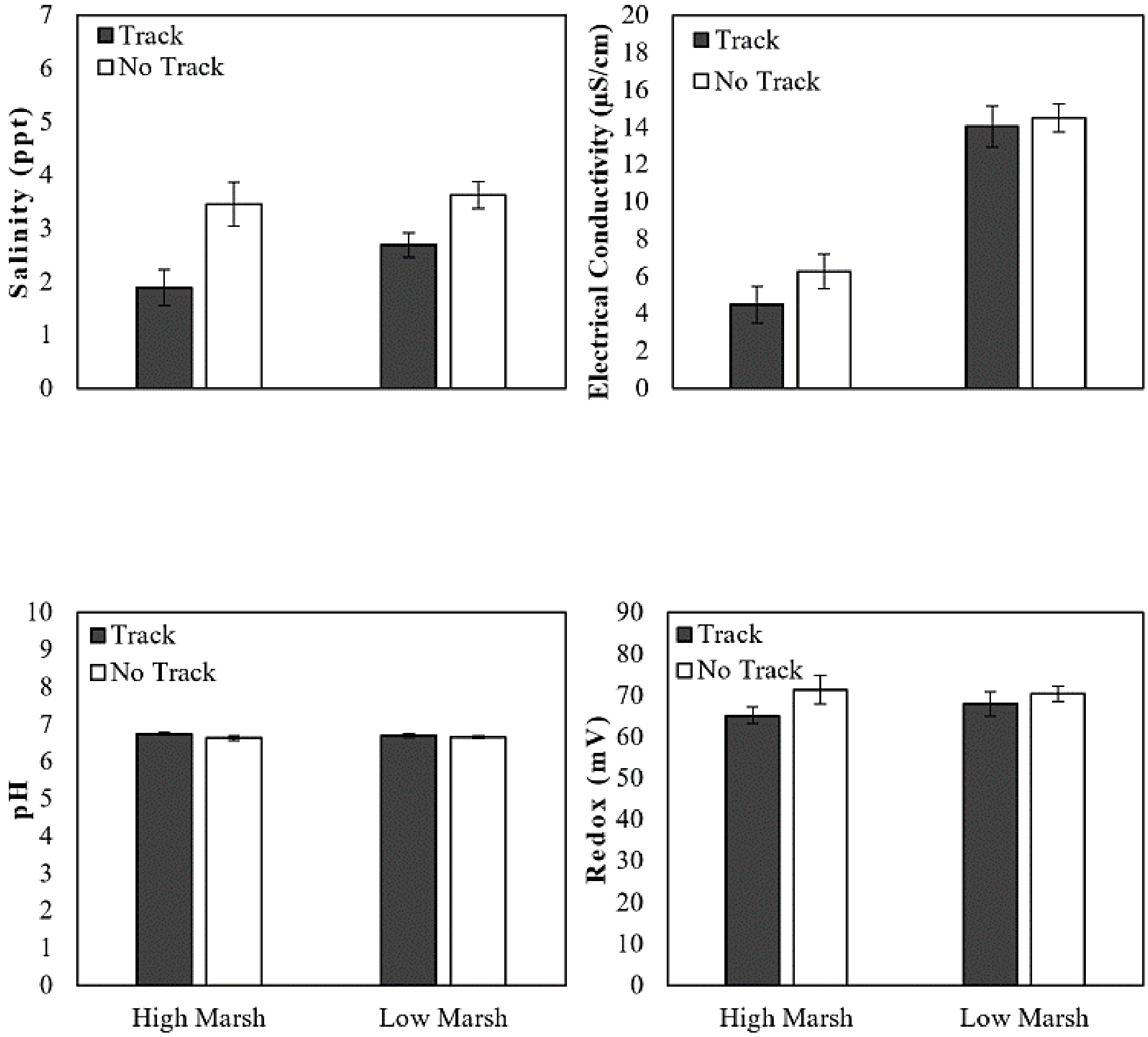

Figure 32: Mean (±SE) salinity, electrical conductivity, pH and redox within impacted (track) and control (no track) areas, within high and low marsh zones at Bermagui.

4.4 Impacts of vehicle disturbance on spatial variables

4.4.1 Elevation

Average elevation, as measured by RTK GPS points at core locations, was found to vary significantly between locations, with Bermagui being on average higher in elevation than Tomakin (0.9 m AHD and 0.6 m AHD respectively). However, elevation did not vary significantly in response to vehicle disturbance across both study locations (Table 21). When the data was separated into high and low marsh zones at Bermagui, no significant effect was found in the high marsh (Table 21). In the low marsh zone, impacted areas were on average higher than control areas (Appendix. IX) This was contrary to expected findings, as visual field observations identified that tracks were associated with depressions in the marsh surface. The statistical result found in this analysis was likely due to sampling bias caused by inherent position of tracks at the study locations, especially at Bermagui, as tracks were simply located in areas higher on the marsh than control areas (refer to figure 15). This sampling bias was addressed by subsequently assessing vehicle damage spatially using transects.

*Table 21: Results from 2-way ANOVA comparing elevation between study locations and between impact and control areas. Bold values indicate significant effects. * denotes where data was square root transformed to normalise distributions.*

Response Variable Predictor variable	*df*	*SS*	*F*	*p*	r^2
Elevation (m AHD)					
Model	3	3.57	47.63	**<0.0001**	0.41
Location	1	3.20	128.26	**<0.0001**	
Vehicle Impact	1	0.03	1.23	0.2680	
Location x Vehicle Impact	1	0.55	0.55	0.2116	
Error	204	5.10			
Elevation (m AHD)					
Model	3	1.03	30.38	**<0.0001**	0.71
Marsh zone (high/low)	1	0.69	61.79	**<0.0001**	
Vehicle Impact	1	0.06	5.48	**0.0246**	
Marsh zone x Vehicle Impact	1	0.05	4.5354	0.0399	
Error	40	0.42			

4.4.2 Micro-topography

Micro-topographical transects measured using RTK-GPS measurements, revealed localised depressions in the marsh surface in association with vehicle tracks (Figures 33 and 34). The depth of depressions varied between locations, with depressions on average 20 cm deep at Bermagui and 10 cm deep at Tomakin. Across some vehicle tracks at Bermagui, micro-topographic impacts were particularly severe, with depressions approximately 30 cm deep (Figure 33 (5) (7)). These fine-scale topographical transects also showed that at Tomakin, elevations on the very edge of vehicle tracks were slightly higher than other areas of un-impacted marsh (Figure 34 (1)(4)(5)).

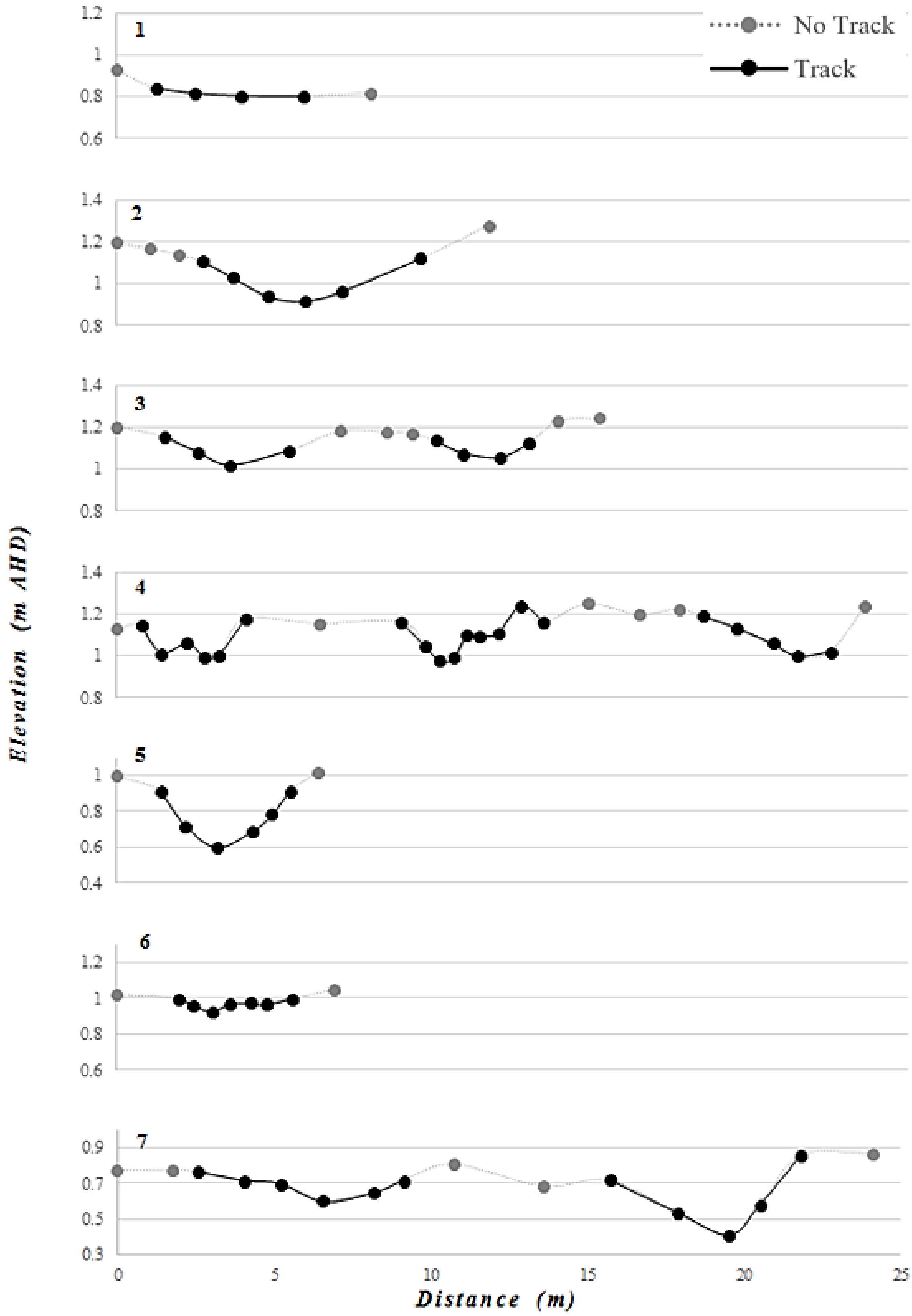

Figure 33: Elevation transects at Bermagui collected via RTK GPS. Black line represents vehicle impacts and grey line represents un-impacted areas

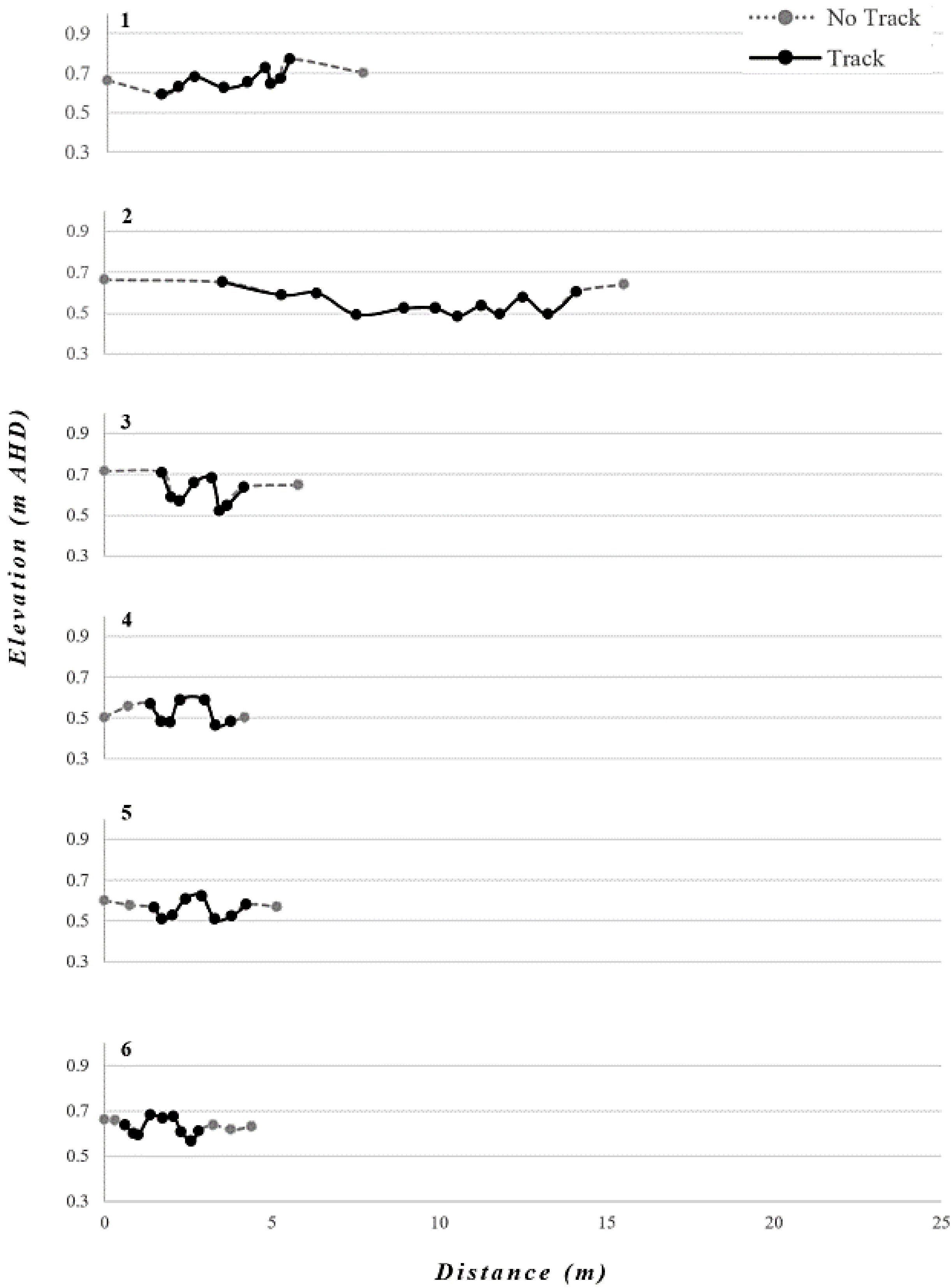

Figure 34: Elevation transects at Tomakin collected via RTK GPS. Black line represents vehicle impacts and grey line represents un-impacted areas

4.4.2 Hydrology

Comparison of flow accumulation surface rasters to digitized polygons of tracks and major vegetation communities revealed that for both locations, tracks generally corresponded to areas of higher flow accumulation (Figures 35 and 37). This trend was more pronounced at Bermagui (Figure 35). This spatial pattern indicated that areas of vehicle disturbance may be more likely to concentrate flow due to localised depressions in the marsh surface. Due to the nature of the flow accumulation algorithm, concentrated flow could include both tidal flow or freshwater flow from precipitation. However, it should be noted that the flow accumulation raster does not model levels of tidal submergence, it simply provides an indication of where flow is most likely to accumulate, based on localised topography. Average flow accumulation values in vehicle-impacted areas were very similar amongst locations, with values of 216 cells and 220 cells at Bermagui and Tomakin respectively (Figures 36 and 38). At Bermagui, vehicle-impacted areas had the highest mean flow accumulation values compared to all other ground cover categories (Figure 36). At Tomakin, flow accumulation was considerably higher in areas of mixed mangrove and lower marsh species than all other categories (Figure 38). Impacted areas had the second highest average flow accumulation values at Tomakin (Figure 38).

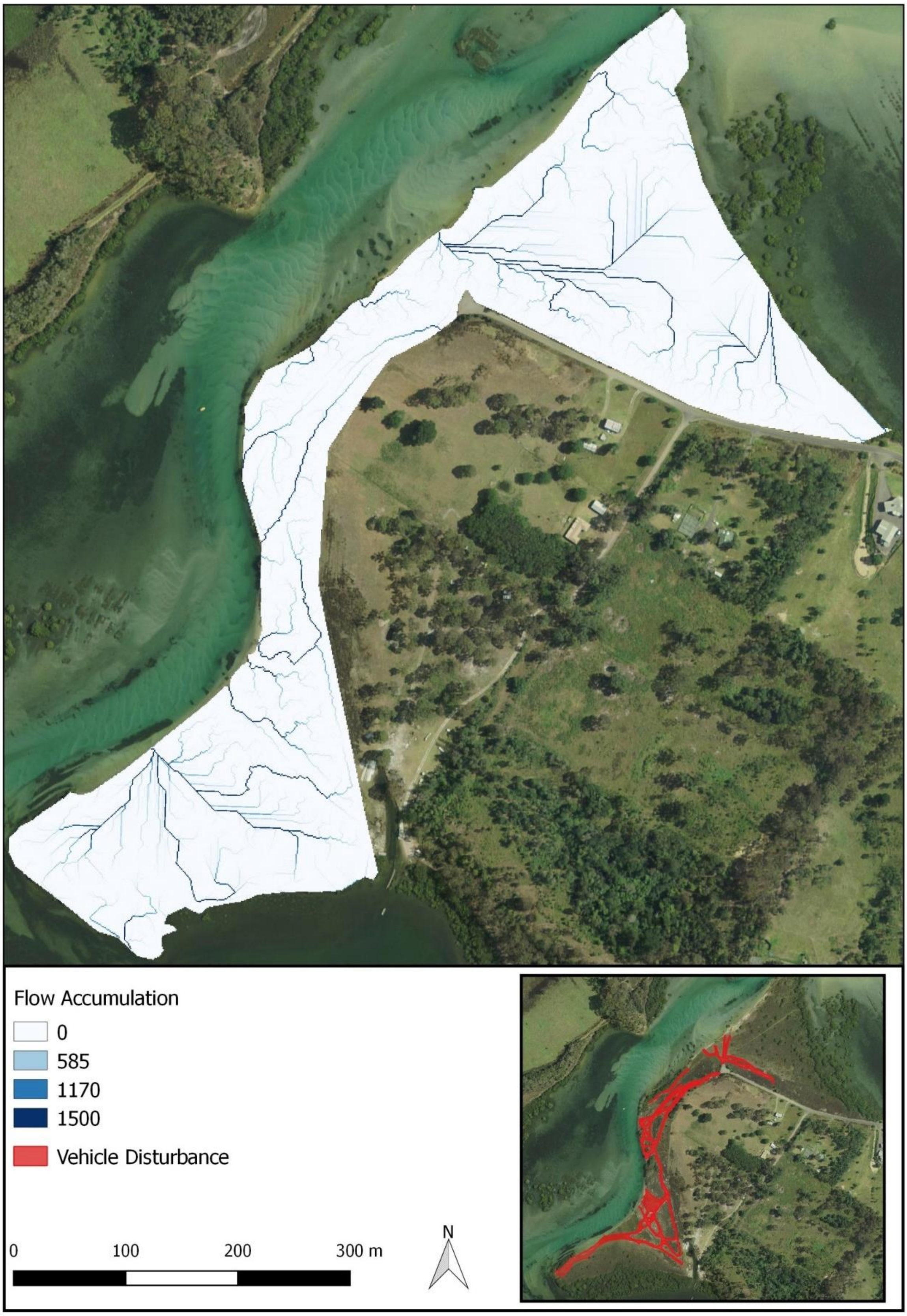

Figure 35: Flow accumulation surface raster at Bermagui overlaid on aerial imagery of the location. Inset map shows location of tracks (Aerial Imagery Source: LPI 2014)

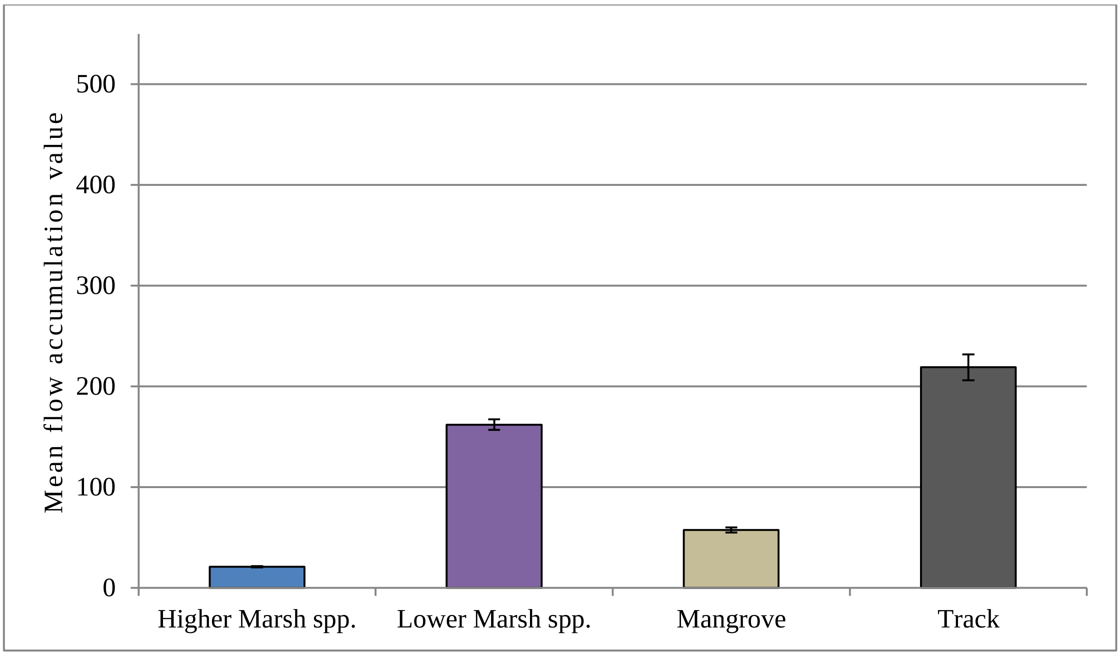

Figure 36: Mean (±SE) flow accumulation values for each ground cover class (track or dominant vegetation community) at Bermagui. Colours of each category correspond to vegetation mapping in figure 18.

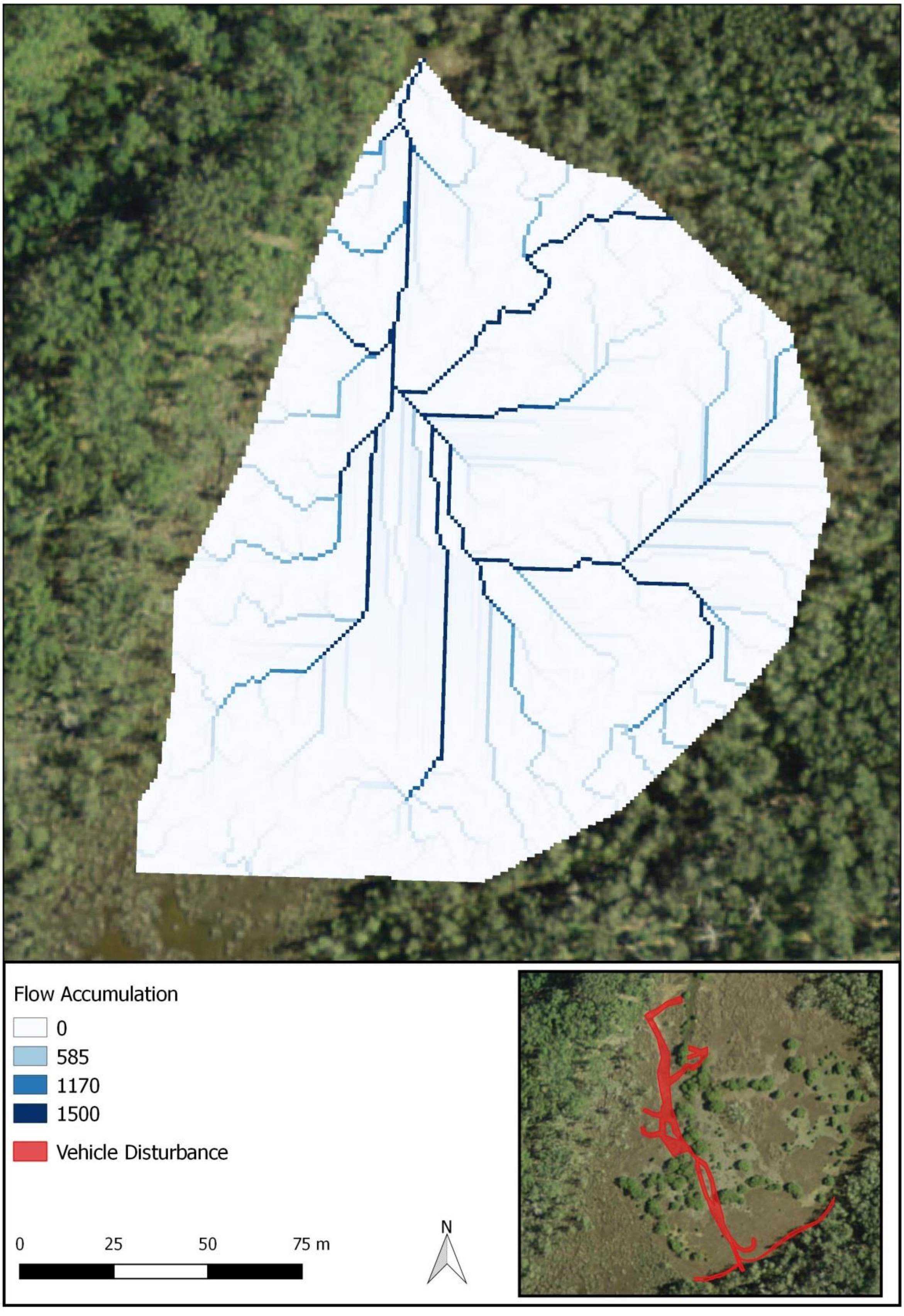

Figure 37: Flow accumulation surface raster at Tomakin overlaid on aerial imagery of the location. Inset map shows location of tracks (Aerial Imagery Source: LPI 2014)

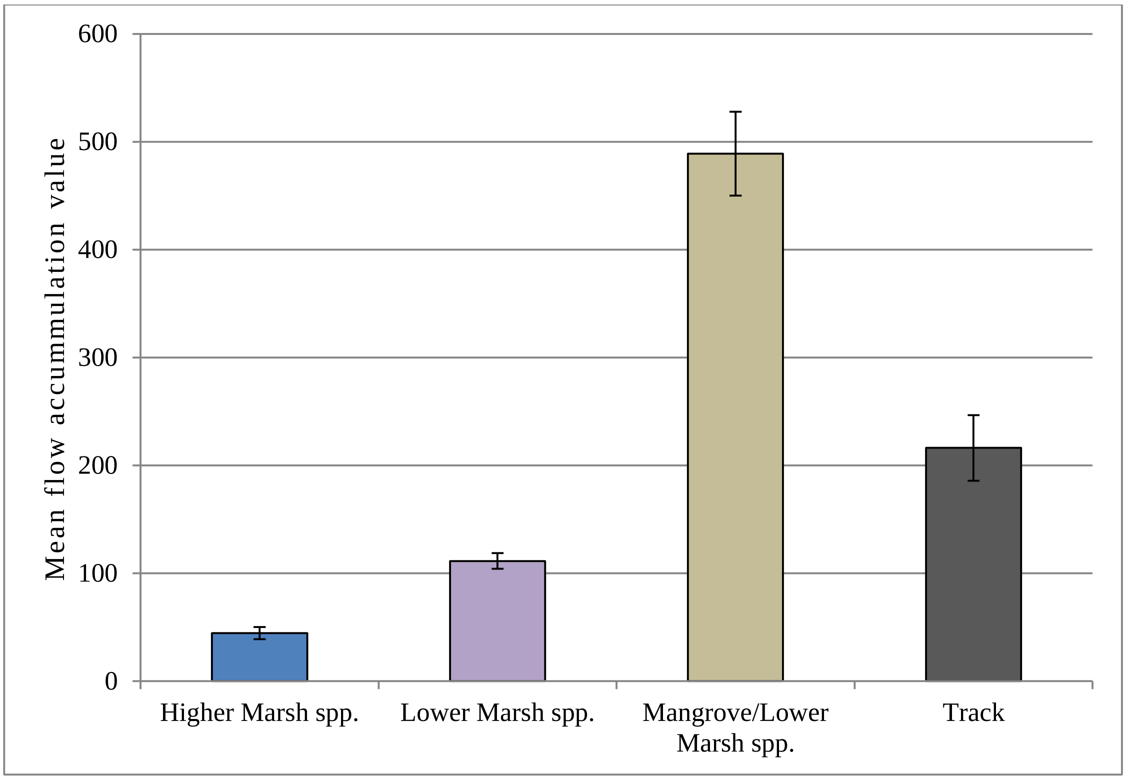

Figure 38: Mean (±SE) flow accumulation values for each ground cover class (track or dominant vegetation community) at Bermagui. Colours of each category correspond to vegetation mapping in figure 19.

5 Discussion

5.1 Impacts of vehicle disturbance on biotic variables

5.1.1 Impacts of vehicle disturbance on vegetation

Using aerial photographic interpretation (API), I found that vehicle use was associated with substantial reductions in total saltmarsh area at both study locations. Vehicle damage was considerably more widespread at Bermagui, with an estimated 1.67 ha of saltmarsh degraded by vehicles (≈12% of saltmarsh at this location). Roper et al. (2011) estimated that saltmarsh on the Bermagui River had an area of 17 ha. The loss of saltmarsh detected at the Bermagui study site from vehicles is therefore highly significant, as it equates to an estimated 9.8 % reduction in total saltmarsh area along this estuary. Saltmarsh at the Bermagui study site comprises a very large proportion of all saltmarsh along the Bermagui river, with an estimated area of 14 ha (including vehicle damage). The extent of vehicle damage at Bermagui was comparable to the area of saltmarsh loss on the George's River, located in southern Sydney (Kelleway 2005). Kelleway (2005) assessed the extent of vehicle disturbance to saltmarsh over time, and showed that vehicle damage increased from 0.2 ha in 1966 to 2.1 ha in 1998. This equated to a loss of approximately 2.5% of saltmarsh area within the George's River (Roper et al. 2011). Vehicle damage at the Tomakin study location was restricted to a much smaller area, with an estimated 0.13 ha (≈ 5 % of the study area) directly impacted by vehicles. Total saltmarsh on the Tomaga River is approximately 46 ha, and therefore saltmarsh loss from vehicle damage at this site was estimated to be only 0.02 % of total saltmarsh area within the estuary. However, the extent of vehicle damage in areas outside of the study locations was not examined, and therefore loss of saltmarsh area due to vehicle damage could be greater than these estimates. It is not known if vehicles have caused damage to other saltmarsh areas along the Bermagui and Tomaga Rivers.

This study found a substantial reduction in vegetation cover (> 90 %) and significantly reduced species diversity (2 ½ times fewer species) in association with vehicle use within saltmarsh. These findings are consistent with those of Wisheu and Keddy (1991); Blionis and Woodin (1999); Kelleway (2005); Howard et al. (2014) and Trave and Sheaves (2014), who all associated vehicle passage with adverse impacts on saltmarsh vegetation. The magnitude of vegetation cover reduction found in this study, was slightly greater than reductions found by Kelleway (2005), who found reductions in the range of 50-75% in areas of high track density. No other studies specifically quantified changes to saltmarsh vegetation cover in response to vehicle disturbance. However, Trave and Sheaves (2014), Blionis and Woodin (1999) and Wisheu and Keddy (1991) visually observed and reported reduced vegetation cover in saltmarsh affected by vehicle passage. Reduced vegetation cover is likely to be a direct impact of vehicle passage within saltmarsh, caused by snapping, squashing or flattening of plants, and damage to root systems. Persistent low vegetation cover subsequent to restriction of vehicles is likely to be caused by indirect effects of vehicle passage, such as unsuitable environmental conditions for plant growth, which are discussed in more detail in Section 5.2 of this chapter.

Of the already limited studies that have investigated vehicle disturbance within saltmarsh ecosytems, only one prior study has examined the impacts to plant species diversity. Blionis and Woodin (1999) studied vehicle impacts within saltmarsh located on the north east coast of Scotland, and found that vehicle disturbance was associated with increased species diversity in high marsh zones, but decreased species diversity in low marsh zones. Increases in species diversity within high marsh tracks were attributed to the fact that there were only a few dominant species outside of tracks (i.e. *Plantago maritima* or *Festuca rubra*) but no dominant species inside of tracks. Drawing on literature from other coastal environments, vehicle disturbance in dune environments is commonly associated with reductions in species diversity (Hosier & Eaton 1980; Pickering & Hill 2007; Thompson & Schlacher 2008), which is consistent with the findings of my research. However, this study is the first to establish a clear relationship between vehicle damage and reduced plant species diversity within saltmarsh ecosystems. Losses in species diversity indicate reduced biodiversity, and have negative influences on overall ecosystem function.

This study showed that vehicle disturbance influenced vegetation composition at both locations. The tufted sedge *Juncus kraussii* and turf grass *Sporobolus virginicus* had extremely low average abundances in impacted areas and were unlikely to occur at all in damaged areas. In contrast, the cover of the succulent forb *Sarcocornia quinqueflora* and shrub *Suaeda australis* was also significantly lower inside of tracks, but these species were more likely to occur in vehicle tracks than un-damaged saltmarsh (Figure 39). Although I have no evidence that *S. quinqueflora* and *S. australis* will cover the vehicle tracks in the future, I did observe many seedlings of these species sprouting within tracks (Figure 39), which indicates that they may be better early-successional colonisers of these denuded spaces than other species, such as *J. kraussii* and *S. virginicus*.   According to Clarke (1993) *J.kraussii* is confined to high elevations within the marsh whilst *S. quinqueflora* predominates within the low marsh. My findings suggest that vehicle use drives a shift in species composition to species characteristic of the lower saltmarsh zone. Kelleway (2005) also found shifts in species composition in response to vehicle damage on the George's River, with the occasional increase of *S. virginicus* and *S. quniqueflora* along the borders of tracks in marsh dominated by *J. kraussii*. Similarly, research undertaken in North Eastern Scotland found that the abundance of the low marsh species *Puccinellia maritima* increased in vehicle tracks, whereas the higher marsh species *Festuca rubra* declined (Blionis & Woodin 1999). Other types of small scale, in-situ disturbances to saltmarsh have been shown to alter species composition. For example, Zedler et al. (1995) found at Kooragang Island in NSW that *Triglochin striatum* was only widespread in areas affected by heavy grazing, but undisturbed areas were dominated by *S. virginicus*. Andersen (1995) identified that *S. marina* was present in areas trampled by humans, but was not present in un-trampled areas in coastal saltmarsh in Denmark. The temporal scale over which such shifts in species composition occur in response to vehicle damage is unknown, but regeneration of the marsh will be limited if compositional shifts are stable through time without management intervention.

Figure 39: S. australis and S. quniqueflora present inside and bordering vehicle tracks, within a larger community of J. kraussii at Bermagui

5.1.2 Impacts of vehicle disturbance on the soil seed bank

Vehicle use across the marsh was shown to negatively influence the diversity and density of the soil seed bank, in addition to the standing vegetation. The density of seeds within the soil was on average 80% lower in tracks than undamaged marsh. Of the limited studies that have investigated the impacts of vehicle disturbance on saltmarsh seed banks, mixed results have been found. Wisheu and Keddy (1991) found that seed density was 90% lower in saltmarsh that had experienced intense vehicle disturbance compared to undisturbed marsh. In contrast, Howard et al. (2014b) found that total number of seeds increased in impacted saltmarsh subsequent to vehicle disturbance.

Extrapolation of seedling densities indicated that vehicle tracks across both locations contained on average 841 seeds/m^2, whereas undisturbed areas contained on average 4027 seeds/m^2. The density of seedlings in undisturbed saltmarsh was consistent with the findings of Murphy (2014), who found that the seed banks of three saltmarsh patches on the southern coastline of NSW, had an average density of 4008 seeds/m^2. Furthermore, I found that the number of different species represented in the seed bank was 2 times fewer in impacted areas for both locations, which was likely to be directly associated with reduced number of seeds.

The large extent at which seed densities were reduced in response to vehicle damage, was unexpected for several reasons. The vehicle tracks are typically narrow, linear features that are flanked by dense swathes of native vegetation (Figure 39). As can be seen from Figure 39 and personal observations at each field site, it was clear that the plants that grow along the margins of vehicle tracks are reproductively mature. The seeds of most of saltmarsh species are capable of dispersing many tens to hundreds of metres during spring tides (Adam 1990; Huiskes et al. 1995; Bakker et al. 1996). Given the very close proximity of adult vegetation to these tracks, and the ability of many seeds to disperse over large scales, it was hypothesised that there would be a similar number of seeds in the soil of tracks and undamaged areas. These results indicate that the impacts of vehicles on resident vegetation, and the ecological stability of the marsh community, are substantially greater than what is evident from losses of vegetation abundance.

The most abundant species' within the seed bank were *J. kraussi, S. repens, S. australis, S.quinqueflora* and *S. marina*, all of which are characteristic and abundant species within the saltmarsh community (Clarke & Hannon 1967; Adam 1981; Clarke 1993). The most abundant species in the standing vegetation were *J. kraussii, S. repens, S. australis*, which indicated a high level of correspondence between seed bank composition and vegetation.

Over half of all emergent seedlings were *J. kraussii*, which suggests that this species played a major role in driving differences in seed density between tracks and adjacent vegetation communities. The high density of *J.kraussii* seeds detected in this study was consistent with other seed bank studies that have shown *Juncus* spp. seedlings to be particularly abundant within saltmarsh soil (Jerling 1983; Shumway & Bertness 1992). Furthermore, previous studies have shown that *J. kraussii* seeds are not spread homogeneously across the marsh, but are clumped very densely at the base of the parent plants (Murphy 2014). Murphy (2014) examined differences in seed bank composition within different saltmarsh vegetation communities and found that *J. kraussii* consistently had significantly higher seed densities within areas dominated by *J.kraussii*. Densities of other saltmarsh species were also higher in areas dominated by their own retrospective species, but this trend was much stronger for *J. kraussii* (Murphy 2014). There are also examples of similar trends within North American saltmarsh, where both Rand (2000) and Smith and Kadlec (1983) found that seed distributions for a range of species paralleled adult plant abundance, indicating localised dispersal and limited movement out of parental environments. These studies are in contrast to the majority literature which suggests that the distribution of vegetation communities has little influence on the spatial distribution of seeds within saltmarsh soils (e.g. Baldwin et al. 1996; Egan & Ungar 2000). These studies, in addition to my own findings, indicate that seed banks in vehicle tracks have lower seed densities than adjacent undamaged marsh, due to low rates of seed arrival and settlement to the soil within tracks.

Clarke and Hannon (1970) investigated the impacts of waterlogging on a range of saltmarsh species typical of the Sydney region and demonstrated that *J.kraussii* sank immediately on contact with water, whereas all other saltmarsh species exhibited some level of buoyancy. The inability of *J. kraussii* seeds to float on water in a tidal ecosystem is likely to constrain the species' dispersal capability, and may largely explain the species' limited ability to disperse to adjacent vehicle tracks. *J. kraussii* was overwhelmingly the most abundant species within the seed bank and contributed most to compositional change at both Bermagui and Tomakin. Consequently, the dispersal capability of *J. kraussii*, in particular the seeds' lack of buoyancy, was likely to play an important role in lowering seed density within the soil of vehicle tracks. Therefore, species with buoyant seeds capable of dispersing long distances with tides, such as *S.quinqueflora* (Clarke & Hannon 1970), may be more likely to recolonise tracks than species with limited seed dispersal, such as *J. kraussii*. The findings of my research support this assumption, as *S. quinqueflora* was found to be the species most commonly recolonising vehicle tracks, whereas *J. kraussii* had considerably low occurrences within tracks.

5.2 Impacts of vehicle disturbance on environmental conditions

Overall, abiotic conditions differed significantly between vehicle tracks and un-impacted saltmarsh at both locations. Vehicle disturbance had greatest influence on physical soil properties, including bulk density, penetration resistance, moisture content, grain size and LOI. Spatial analysis identified changes to micro-topography and hydrology in response to vehicle disturbance. In contrast, vehicle disturbance had very minor influence on chemical soil properties, with redox being the only factor that was significantly different in areas of vehicle disturbance. These results indicate that physical soil properties, micro-topography and hydrology are likely to be the key environmental factors limiting vegetation regeneration within vehicle tracks.

5.2.1 Impacts of vehicle disturbance on physical soil properties

Although physical soil conditions varied between study locations, with drier, sandier soil at Bermagui, impacts of vehicle disturbance on soil properties followed the same trajectory at each location. These physical soil properties included moisture content, bulk density, penetration resistance, LOI and grain size. Impacts on soil properties were shown to be greater on the surface at depths of 0-1.5 cm compared to sub-surface depths of 5.5-7 cm.

Soil compaction, as indicated by bulk density, was significantly higher in areas of vehicle disturbance at both locations, (28% and 17% higher at respective surface and sub-surface depths).

These findings were consistent with the findings of Kelleway (2005) and Blionis and Woodin (1999), who also detected significantly higher soil bulk densities within vehicle tracks. Soil compaction was shown to be more severe within tracks at Bermagui, as indicated by higher mean bulk density and soil penetration resistance. High soil compaction within tracks at Bermagui is likely due to the long period of time over which human activity has occurred at this site.

Soil compaction has been widely reported as an impact of vehicle passage within agricultural studies (Håkansson et al. 1988; Smith & Dickson 1990; Raper 2005). These studies have demonstrated that soil compaction occurs when a vehicle passes over the soil, which leads to reduced volume available for air and water, as mineral components are pressed closer together (Raper 2005). Soil compaction, as indicated by high bulk density and penetration resistance, negatively influence plant growth by hindering root system development, decreasing accessibility of nutrients and increasing loss of soil nutrients via leaching and runoff (Bécel et al. 2012; Nawaz et al. 2013a). Soil compaction may also indirectly affect revegetation, by reducing moisture penetration (from rainfall and tides) and increasing erosion (Raper 2005).

Soil moisture content was lower in areas of vehicle disturbance, for both soil depths analysed. Lower moisture contents in vehicle-impacted areas were most likely due to higher bulk densities, as less pore space is available for retention of water within dense soils (Archer & Smith 1972). Blionis and Woodin (1999) and Kelleway (2005) also found lower soil moisture contents in saltmarsh affected by vehicle disturbance, which suggests that this effect is a common trend.

Within this study, I found that soil organic matter was generally lower in vehicle tracks, as indicated by lower % LOI. Larger grain sizes were also associated with vehicle disturbance, indicating a greater proportion of sandy substrates compared to organic rich muds within tracks. Reduced organic content within vehicle tracks is likely to be a result of reduced vegetation abundance and thus lowered organic inputs to the soil via the root system and leaf litter. Soil organic matter is a key indicator of soil quality as it is associated with a number of key processes that influence plant growth, including respiration, denitrification and phosphorous absorption (Doran & Parkin 1994; Dexter 2004). Wetland sites with low levels of soil organic matter have been linked to low growth and survival of plant species (Bruland & Richardson 2006). This indicates that any plants that recolonise tracks in future – both those that naturally regenerate or seedlings planted as part of rehabilitation measures – may grow poorly if the organic content within the soil is too low and therefore unsuitable for their growth and survival.

At Bermagui, differences in physical soil properties between vehicle damaged and adjacent vegetation, were shown to be more distinct in the high marsh zone. Despite this, soil properties in vehicle tracks across both high and low marsh did not vary significantly from one another. Greater differences between physical soil properties (in particular soil moisture and LOI) in the high marsh, were attributed to higher marsh areas naturally containing greater levels of soil organic matter and moisture content.

5.2.2 Impacts of vehicle disturbance on chemical soil properties

Chemical soil properties (including salinity, electrical conductivity, pH and redox) were not identified as important drivers of abiotic change in response to vehicle disturbance. Salinity and electrical conductivity were lower inside vehicle tracks, but these differences were not significant. This was contrary to expected results, which was that salinity and electrical conductivity would be higher in tracks due to greater exposure to solar radiation and thus increased evaporation and retention of ions within the soil. Lower values of salinity and electrical conductivity may be attributed to pooling of freshwater from precipitation, which may occur due to localised depressions in the marsh surface.

Blionis and Woodin (1999) also detected reduced salinity in response to vehicle disturbance, whereas Howard et al. (2014b) and Kelleway (2005) did not detect any changes to electrical conductivity or salinity. Lowered salinity is unlikely to hinder the growth of saltmarsh vegetation in the long term. Although halophytic plants can tolerate saline conditions, they do not require elevated salinity levels to complete their lifecycle (Clarke & Hannon 1970; Greenwood & MacFarlane 2006; Naidoo & Kift 2006). Despite this, decreased salinity may impact vegetation by increasing competition between species (Pennings & Callaway 1992; Greenwood & MacFarlane 2006; Greenwood & MacFarlane 2009). For example, Greenwood and MacFarlane (2009) found that in areas of reduced salinity stress, invasive species *Juncus acutus* may outcompete *Juncus kraussii*. Incursion of plants with reduced salinity tolerances was not detected within vehicle tracks throughout this study, even at Tomakin where *Juncus acutus* was present.

Vehicle damage had no influence on pH, with little variation found between measurements across both locations, indicating that the soil has not undergone acidification or alkalisation in response to vehicle disturbance.

Redox potentials were found to be lower in areas of vehicle impact at both sites, which was consistent with anticipated results. Redox potentials indicate levels of soil aeration and can also detect waterlogging and anaerobic conditions within saltmarsh soils (Adam 1990). Lowered redox potentials in impacted areas are likely to be directly attributed to greater soil compaction in vehicle tracks (Nawaz et al. 2013). Soil compaction causes reduced oxygen diffusion, which can lead to anoxic conditions (Renault & Stengel 1994; Schnurr-Pütz et al. 2006). Lowered redox potentials have important implications for rehabilitation, as soil aeration is regarded an important factor affecting plant performance and the zonation of vegetation within coastal marshes. (Armstrong 1967; Howes et al. 1980). Although redox was found to be significantly lower in tracks, the difference found was not of high magnitude. Redox potentials were on average 7 mV and 16 mV lower in tracks at Bermagui and Tomakin respectively. This difference is minor considering that redox potentials within saltmarsh soil have been shown to vary at much greater magnitudes between vegetation zones and in response to tidal cycles. For example, Armstrong et al. (1985) and Davy et al. (2011) showed that redox potentials could range between approximately -200 and 500 mV within saltmarsh soils. Although redox in this study was found to be lower in tracks, it is likely that the magnitude of reduction was not great enough to play a major role in limiting natural regeneration in damaged areas.

Trends in chemical soil properties found in this study must be interpreted with care. Chemical soil properties are likely to vary significantly in response to precipitation, tides and temperature. For example, after recent rainfall events, freshwater may accumulate in tracks and therefore lower salinity. Conversely, dry, hot conditions subsequent to tidal inundation may elevate salinities through increased evaporation, especially in tracks that lack shading from vegetation. The conditions on the day of sampling in this study may have just been conducive to lower salinity, electrical conductivity and redox in tracks, but this may not always be the case.

5.2.3 Impacts of vehicle disturbance on micro-topography and hydrology

Average elevation, as measured by RTK-GPS points at core locations, did not significantly differ between vehicle tracks and non-impacted saltmarsh. This was most likely due to a sampling bias caused by the position of vehicle tracks in areas of the marsh that were generally higher. In order to overcome such sampling bias, I measured elevation along a set of high resolution transects, that traversed the marsh and intersected the vehicle tracks at right angles. I found that there was a clear spatial pattern of lowered elevation in in response to disturbance. Depressions associated with vehicle tracks were on average much deeper at Bermagui (≈ 20 cm), compared to those at Tomakin (≈ 10 cm), with some depressions as deep as 30 cm. Changes to micro-topography found in this study, were much greater than those found by Kelleway (2005) on the George's River. Kelleway (2005) compared rut depths caused by BMX, trail bike and 4WD vehicles and found depressions of approximately 2 cm, 3 cm and 7 cm respectively. Depressions on the marsh surface were likely to be caused by soil compaction processes associated with vehicle passage. Both myself and Kelleway (2005) found slight raises in elevation on the very edge of vehicle tracks, which were higher in elevation than surfaces further away from tracks. This trend was most likely caused by erosive effects of vehicle passage, whereby tyres scour the marsh surface, causing build-up of soil either side of tracks.

Hydrologic modelling detected correspondence between vehicle tracks and areas of high flow accumulation. This suggests that pooling of water is common within tracks, and impacted saltmarsh is likely to experience higher levels of waterlogging than surrounding vegetation. Hydrologic modelling also indicated that vehicle disturbance may facilitate the formation of stream networks across the marsh surface. Changes to hydrology were more extreme at Bermagui, which was consistent with micro-topographical trends detected during transect analysis. Severe pooling of water within vehicle tracks at Bermagui was visually observed during multiple site visits, which is consistent with findings of higher flow accumulation within tracks. Figure 40, taken during vegetation surveys completed as part of this study, shows the complete submergence of a vehicle track within the higher marsh zone at Bermagui. Accumulation of water within vehicle tracks is likely to adversely affect plant growth and survival in these areas. Although saltmarsh species are tolerant of periodic inundation associated with tides, many saltmarsh species can only withstand short periods of submergence, due to anaerobic conditions associated with waterlogging (Mendelssohn & McKee 1988; Adams & Bate 1994; Huckle et al. 2000).

Figure 40: Water pooling in a vehicle track in the higher marsh zone at Bermagui, photo taken as part of vegetation surveys

5.3 Interaction between biotic and environmental factors

5.3.1 Influence of environmental conditions on vegetation

Physical soil properties, micro-topography and hydrology were identified as the most important abiotic factors driving change between vehicle tracks and un-impacted saltmarsh. These factors have important implications for the persistence and future regeneration of vegetation within tracks. Greatest correspondence in environmental conditions was detected between vehicle-impacted saltmarsh and lower marsh communities at Bermagui. Furthermore, soil moisture content and LOI within vehicle tracks at Bermagui, was not significantly different from soil in lower marsh zones. At Tomakin, the greatest correspondence in environmental conditions was detected between vehicle tracks and areas of mangrove cover. These trends indicate that vehicle disturbance may cause soil conditions in vehicle damaged areas to become more similar to the environmental conditions of lower marsh and mangrove zones.

These trends have important implications for rehabilitation of disturbed sites, as environmental conditions are likely to influence vegetation community composition within rehabilitated areas. Changes to environmental conditions, such as hydrology and physical soil properties, are likely to be associated with shifts in plant community composition in vehicle tracks. Typical lower marsh species *Sarcocornia quinqueflora,* was shown to be the most abundant species in vehicle tracks across both locations. At Bermagui, *S. quinqueflora* and *S. australis* were found to be more likely to occur inside tracks than any other areas. These results suggest that the environmental conditions in vehicle tracks may now favour the growth of plant species that typically grow in the lower marsh. Lower marsh species may be exposed to less tolerable soil conditions, as a result of occurring lower in the tidal frame. For example, processes of wetting and drying are a natural cause of soil compaction (Kozlowski 1999), and thus lower marsh species, that experience more frequent wetting and drying, may have a higher tolerance for compact soil conditions. Furthermore, vehicle tracks have been shown to have greater potential for water pooling, and thus species regenerating in vehicle tracks would have to withstand greater levels of surface water-logging. Higher marsh species, such as *Juncus kraussii,* are typically associated with organic-rich, fine grained soils, whereas lower marsh species have been shown to occur in areas with comparatively less soil organic matter (Clarke & Hannon 1967; Vince & Snow 1984). Vehicle tracks were shown to be associated with coarser grained soils, with reduced organic matter, suggesting that these areas may now favour the growth of lower marsh species at the expense of higher marsh species.

The environmental conditions in vehicle tracks at Tomakin were most similar to environmental conditions in areas of mangrove cover. Growth of *Avicennia marina* was visually observed inside vehicle tracks at Tomakin (Figure 41). It is unlikely that these areas would have been dominated by mangroves prior to vehicle disturbance, as it would have been too difficult for vehicles to pass over them. Therefore, changes in environmental conditions associated with vehicle disturbance, such as depressions in the marsh surface, may favour the growth of mangroves over saltmarsh species within vehicle tracks at Tomakin.

Figure 41: Growth of mangroves (Avicennia marina) in areas of vehicle disturbance at Tomakin.

5.3.2 Influence of environmental conditions on the seed bank

Surface attributes influence whether seeds become entrapped in the soil or are dispersed elsewhere by wind or water (Chambers & MacMahon 1994; Zabinski et al. 2000). Seeds are less likely to become entrapped in compacted soils (Stamp 1989; Zabinski et al. 2000). Soils in areas affected by vehicle disturbance were significantly more compact, with higher bulk densities at both locations and higher penetration resistance at Bermagui. Lowered seed densities in tracks could be influenced by higher soil compaction, by lowering the ability of seeds to become incorporated into the soil. Furthermore, settlement of seeds dispersed by water may be more common in vegetated areas than bare ground (Zabinski et al. 2000), because vegetation reduces water flow velocity and thus increases settlement rates of seeds (Merritt & Wohl 2002). In a seed dispersal experiment conducted in a flume channel, Merritt and Wohl (2002) found a smaller number of seeds deposited in areas of high flow velocity compared to areas of slow velocity. Therefore, accumulation of seeds may be more common on vegetated surfaces, compared to bare ground typical of vehicle disturbance.

5.4 Limitations and future research

A key limitation of this study was the level of replication within the location treatment, with only two locations examined. Very similar trends were detected in association with vehicle disturbance at the two locations, and thus the impacts of vehicle disturbance to saltmarsh ecosystems can be generalised to a certain extent. Considering that vehicle use in saltmarsh is considered a serious threat around the globe (Adam 2002), further research should encompass a broader range of locations, to effectively generalise the impacts of vehicle damage for a wider range of saltmarsh ecosystems.

Due to the time constraints of this research, the sampling frequency for a number of key variables was considered a major limitation. Many factors measured throughout this study, vary considerably over different time scales. For example, salinity and redox vary considerably with precipitation and tidal influence, and vegetation and availability of seed are likely to vary substantially with season. These variables were only assessed once and therefore this study was not able to capture variation over time. In order to elucidate the long term impacts of vehicle use on the attributes of the soil and seed bank, evaluation of changes over multiple seasons and standardised points of time (e.g. not directly after a rain event or spring tide) is required.

The use of LiDAR data to model hydrology within this study was limited by the accuracy of the data. The vertical accuracy of the LiDAR data (± 0.30 m) meant that small scale topographical variations in response to vehicle damage may have not been detected. Comparisons of transects taken by RTK-GPS to corresponding values on the LiDAR DEM, showed that LiDAR data was effective at detecting topographical trends associated with vehicle disturbance at Bermagui, but was less effective at detecting these trends at Tomakin (Appendix V). Therefore, hydrological trends associated with vehicle disturbance at Tomakin must be interpreted with care.

Aerial photograph interpretation (API) was useful for estimating the extent of vehicle damage at both study locations. However, this study did not attempt to quantify the extent of vehicle damage to saltmarsh in locations other than the study sites. Therefore, future research could utilise API to quantify the extent of vehicle damage within other areas of saltmarsh along the Australian coastline, to identify and prioritise areas that require protection from vehicle disturbance.

Future research should also focus on monitoring rehabilitation of vehicle damaged saltmarsh. In particular, studies should compare the effectiveness of both passive and active rehabilitation strategies in saltmarsh affected by vehicle disturbance. For example, rehabilitation success could be compared for a number of different treatments including; where vehicles have been excluded and no other remediation technique has been applied, where unsuitable soil conditions (i.e. soil compaction) have been remediated but no replanting has occurred, where vegetation has been replanted but soil condition has not been remediated; and where soil conditions have been remediated and replanting has occurred. Comparing these different strategies would provide important information regarding the most suitable method for rehabilitation of vehicle damaged saltmarsh.

5.5 Recommendations for rehabilitation

The first and most crucial recommendation for rehabilitation is to restrict vehicle access to saltmarsh experiencing degradation from vehicle usage, given the substantial damage that is evident to native vegetation, the seed bank and the soil environment. Educational signage, outlining the ecological importance of saltmarsh and relevant protective legislation, should be placed in areas prone to vehicle damage (Laegdsgaard et al. 2009; Dalby-Ball & Olson 2012). In addition to this, information on any rehabilitation works in the area should be included as part of educational signage.

At the Bermagui study site, vehicle access has already been restricted with fencing. Despite this, there is still evidence of motorbike and trail bike access, because these vehicles are smaller and can breach fencing. This area would highly benefit from educational signage, as the area is commonly used by the public to access the foreshore. This area may also benefit from maintenance of established walking paths, due to its popularity for recreational foreshore activities such as walking, fishing and kayaking. Elevated walkways such as boardwalks have relatively low impact on vegetation communities and have proved successful in many wetland systems (Laegdsgaard et al. 2009). However, construction of boardwalks may not always be a feasible option. Designated pathways consisting of bare ground could be used at Bermagui to minimise impact to sensitive communities. These pathways could consist of some remnant vehicle tracks, of reduced size, that lead directly to the foreshore. Public should be encouraged to use these designated tracks and all other disturbed areas should be remediated.

At the Tomakin study site, there is less evidence of use by the public for recreational foreshore activities, as there is no clear access to the foreshore. The site is in a more secluded location in comparison to Bermagui, as entry is via an unmaintained dirt-road, only accessible by 4WD vehicles. Vehicle disturbance at this location was in the shape of 4WD tracks, suggesting that damage at this location is mostly caused by this type of vehicle. Damaged saltmarsh at this area is likely to highly benefit from fencing to restrict vehicles, and the type of fencing should be capable of excluding smaller off-road vehicles such as motorbikes and trail bikes. As there is little evidence of other types of recreational use, educational signage may not be beneficial or necessary if vehicles can be successfully excluded.

The success of vegetation rehabilitation depends on both the availability of target species and their seeds and suitable abiotic conditions (Bakker et al. 1996). Although at both Tomakin and

Bermagui the target species were in close proximity to disturbed areas, my research revealed that seed densities in vehicle tracks were considerably reduced. Furthermore, abiotic factors such as physical soil condition and hydrology were significantly altered inside of tracks. These factors are likely to negatively influence the success of any passive rehabilitation measures.

Rehabilitation of vegetation in disturbed areas will be most successful in areas where the environment has been made suitable for natural colonisation. Such colonisation is likely to arise from the seed bank (Green et al. 2009; Murphy 2014) or from adjacent plants that spread into the area from vegetative growth of roots or stems (Burchett et al. 1999a; Laegdsgaard 2002). I showed that the soil of vehicle damaged saltmarsh had considerably lower densities of seeds, and therefore any natural recovery of vegetation in these areas may need to develop primarily from vegetative spread from rhizomes or stolons of adjacent plants (Allison 1995; Laegdsgaard 2002). Although regeneration via vegetative spread has the potential to contribute to rehabilitation of vehicle tracks, it was not observed to be regularly occurring at the saltmarsh sites studied. In the limited areas where vegetation recovery was occurring in tracks, the species' growing back in tracks were usually different to the directly adjacent vegetation (i.e. *S. quinqueflora* and *S. australis* were establishing in vehicle tracks within areas dominated by *J.kraussii*) (Figure 39). These observations suggest that recovery within vehicle tracks may be due to both seedling establishment and vegetative spread. Seeds of these typical lower marsh seeds are capable of dispersing to vehicle tracks via tides, and may be more successful at establishing in these areas than surrounding *J. kraussii*, due to greater tolerances of environmental conditions within tracks. Vegetation regeneration in tracks is therefore likely to be a result of further seedling establishment and vegetative spread of these typical lower marsh species. In vehicle tracks completely devoid of vegetation, seeds are either not dispersing to these areas, or are simply not being incorporated into the seed bank. Therefore, recolonization of vegetation is not likely to occur in these areas. Overall, low seed densities within vehicle tracks may substantially limit regeneration, as seedling establishment is likely to play an important role in the initial recolonization of bare saltmarsh.

High levels of soil compaction, are also likely to be preventing re-establishment of saltmarsh vegetation species within vehicle tracks. Although, levels of soil compaction may naturally decline over time if vehicles are excluded, severely affected areas may require active measures such as mechanical loosening of the soil. Sediment profile restructuring is likely to be beneficial within tracks associated with deep elevational depressions in the marsh surface (Green et al. 2009). Rebuilding the soil profile in these areas may prevent pooling of water, which may also indirectly alleviate soil compaction. Further to soil compaction and altered micro-topography, soil in tracks was shown to be of poorer quality, indicated by reduced organic content. Amelioration of the soil to increase organic content may also make soil more suitable for vegetation regeneration. For example, Paul and Farran

(2010) demonstrated that addition of mangrove mulch to sediment positively influenced rates of saltmarsh regeneration.

Alleviation of soil compaction in vehicle tracks is also likely to increase entrapment of seeds into the soil, and thus have positive impacts for vegetation regeneration through increased seedling establishment. However, both this study and research undertaken by Murphy (2014) showed that seedling dispersal out of parental environments may be limited, especially for the dominant saltmarsh species *Juncus kraussii.* This has negative implications for potential rehabilitation of the marsh, as it suggests that seed dispersal into bare areas may be limited. Further active rehabilitation may be required to facilitate recovery of vehicle damaged saltmarsh, especially if the rehabilitation objective is to regenerate vegetation in a short time frame. Active revegetation measures could be used to speed up the recovery process, which may facilitate further natural recolonization by ameliorating harsh environmental conditions (Chapman & Roberts 2004). Revegetation options include sowing of seed, cultivation from seedlings, transplantation of whole plants or transplantation of shoot cuttings (Laegdsgaard 2006). Rehabilitation using active revegetation measures may be imperative if the objective is to restore a particular species. My research showed that the environmental conditions in vehicle tracks are likely to favour the growth of lower marsh species rather than higher marsh species such as *Juncus kraussii.* It was also shown that *J. kraussii* seeds exhibit limited dispersal away from the base of parent plants. If the rehabilitation goal is to restore cover of *Juncus kraussii,* active revegetation techniques, in conjunction with remediation of the soil environment, are likely to be the most successful options.

6 Conclusions

The overarching aim of this thesis was to assess the impacts of vehicles on saltmarsh ecosystems, and provide insight into potential rehabilitation strategies. My research demonstrated that vehicles adversely impact saltmarsh ecosystems in a number of ways.

Vehicle disturbance was associated with severe denudation of vegetation, with significantly reduced vegetation cover within tracks. Vegetation species diversity was also demonstrated to be reduced in areas of vehicle damage. Vegetation species composition was altered in response to vehicle damage, with impacted areas more likely to comprise species characteristic of the lower marsh, in particular, the succulent forb *Sarcocornia quinqueflora* and shrub *Suaeda australis.* These compositional changes were likely to be attributed to the dispersal mechanisms of these species and shifts in abiotic conditions.

The soil seed bank was adversely impacted by vehicles, with considerably lower seed densities within tracks. Species diversity of seeds within the soil was also significantly lower in areas of disturbance. These findings have important implications for rehabilitation, as saltmarsh areas with a depauperate and species-poor seed bank may have low rates of regeneration, and rely on external seed inputs or vegetative propagation for recovery (Fourie 2008; French et al. 2011).

Vehicle damage was shown to significantly alter the abiotic environment. Vehicle disturbance was associated with severe soil compaction and reduced soil organic matter. Such soil conditions have significant influence on ecological function of the saltmarsh and were identified as major factors limiting regeneration in impacted areas. Vehicle disturbance was also associated with localised depressions in the marsh surface and thus altered hydrological conditions. Altered hydrology was also identified as major barrier to natural recovery, because pooling of water in tracks may generate unfavourable soil conditions, and thus limit vegetation regeneration. Chemical soil properties were not substantially influenced by vehicle disturbance, and were thus not deemed to be major factors suppressing recovery of vegetation.

Investigation of the impacts of vehicle damage to saltmarsh environments revealed that passive rehabilitation strategies may not be effective at the Bermagui and Tomakin saltmarsh sites. Recommended rehabilitation strategies involve remediating unsuitable soil conditions, to facilitate natural recolonization of vegetation and replenishment of the seed bank. If the rehabilitation objective is to recover vegetation communities within a short period of time, active revegetation measures may be required, due to current low seed densities within tracks.

7 References

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8 Appendices

Appendix I

Signage at the Bermagui saltmarsh location, by the Bermagui Historical Society

Appendix II

List of species detected in the standing vegetation at Bermagui. N = native species, A = alien species, U = unknown species

Species	Type
Aegicerus corniculatum	N
Avicennia marina	N
Ficinia nodosa	N
Juncus kraussii	N
Limonium austral	N
Lomandra longifolia	N
Samolus repens	N
Sarcocornia quinqueflora	N
Sporobolus virginicus	N
Sueada australis	N
Unidentified poaceae	U
Wilsonia backhousei	N

Appendix III

List of species detected in the standing vegetation at Tomakin. N = native species, A = alien species, U = unknown species

Species	Type
Avicennia marina	N
Juncus acutus	A
Juncus kraussii	N
Limonium austral	N
Samolus repens	N
Sarcocornia quinqueflora	N
Selliera radicans	N
Sporobolus virginicus	N
Sueada australis	N

Appendix IV

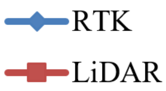
List of species detected in the seed bank across both locations sorted alphabetically.

N = Native species, A = Alien species, U = Unknown species

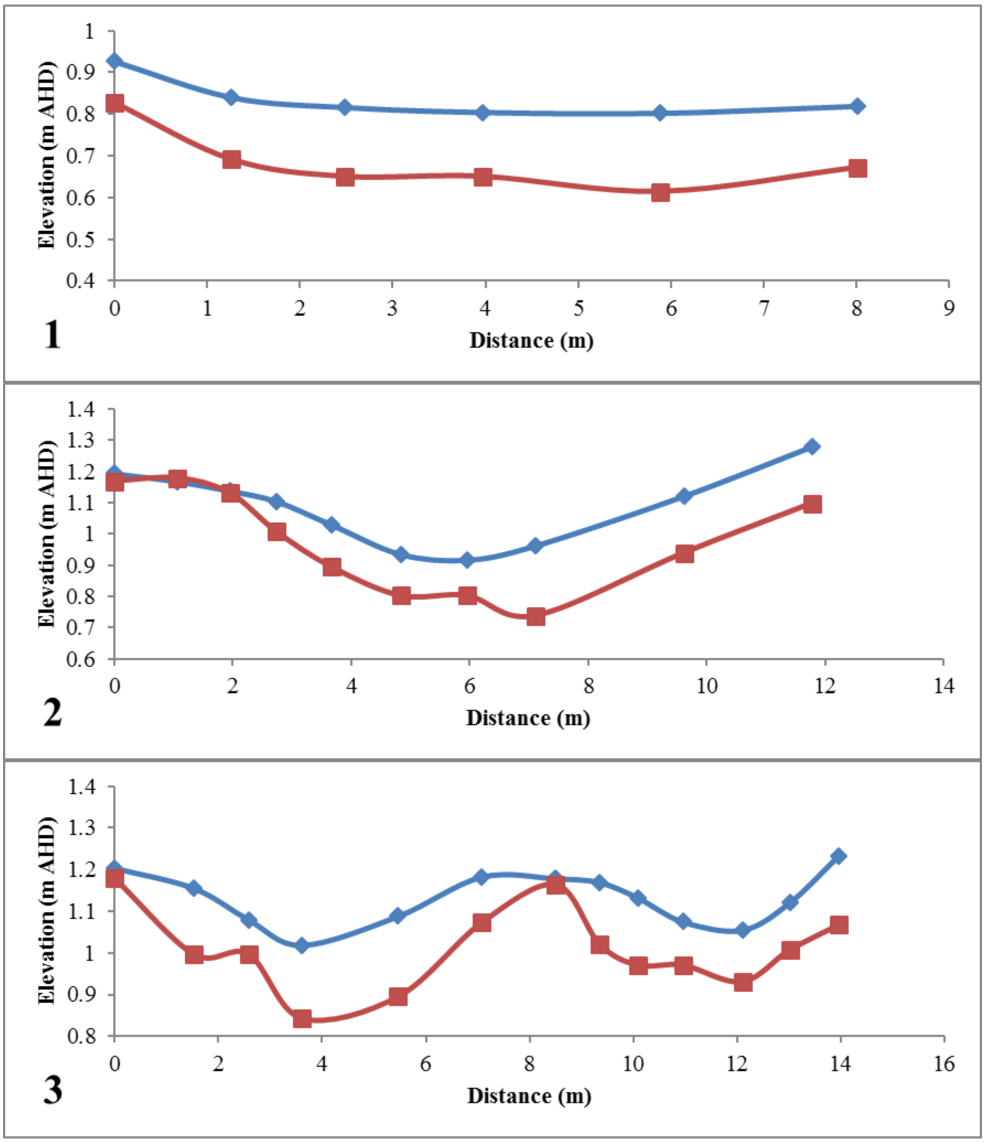
Species	Type
Asteraceae spp.	A
Conyza bonariensis	A
Senecio madagascariensis	A
Apium prostratum	N
Baumea juncea	N
Chenopodium spp.	N
Cotula australis	N
Cyperaceae spp.	N
Juncus kraussii	N
Lobelia anceps	N
Samolus repens	N
Sarcocornia quinqueflora	N
Selliera radicans	N
Spergularia marina	N
Sporobolus virginicus	N
Sueda australis	N
Triglochin striata	N
Medicago spp.	A
Oxalis spp.	N
Poaceae unknown 1	A
Poaceae unknown 1	U
Unknown dicot 2	U
Unknown dicot 3	U
Unknown dicot 4	U

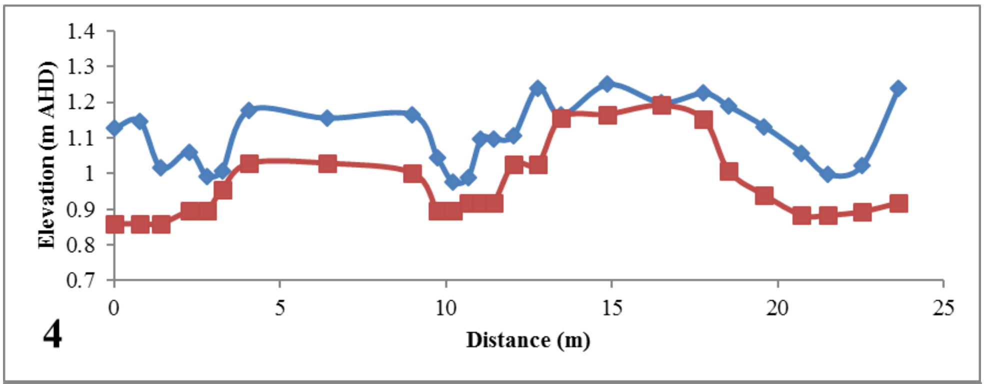
Appendix V

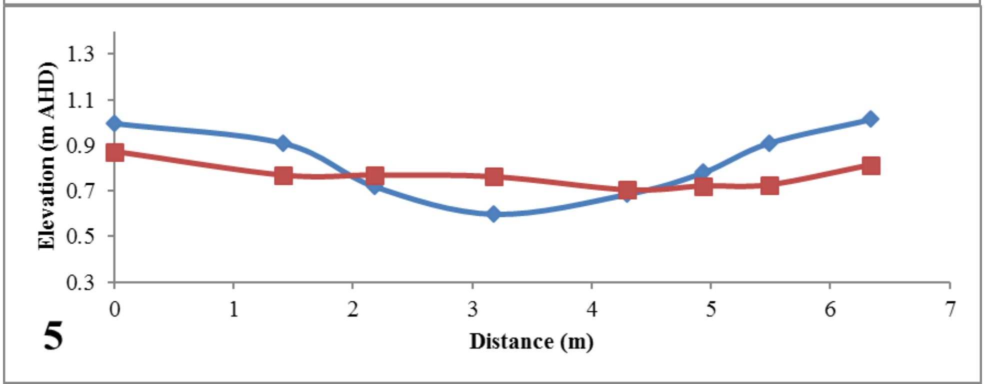
Comparison between transects across vehicle tracks taken with RTK GPS and LiDAR DEM values. Numbers correspond to transect numbers shown in figure 15.

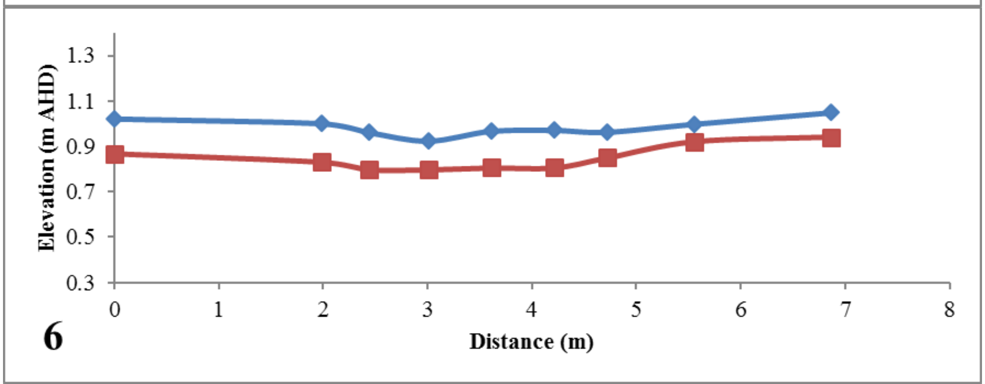


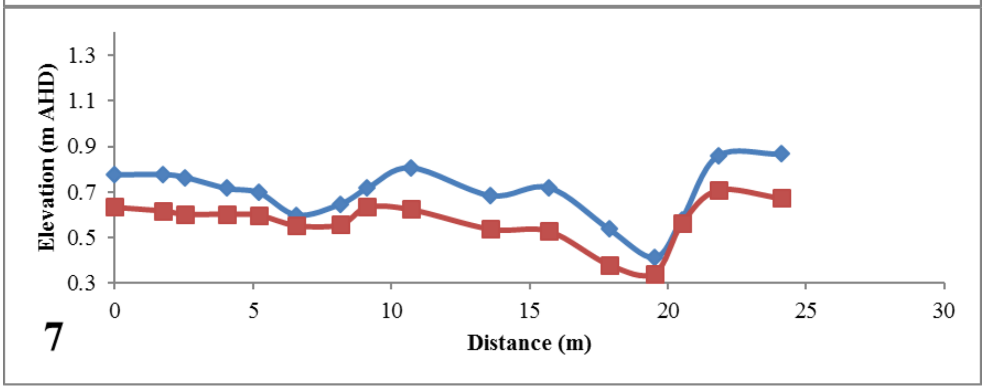
Bermagui



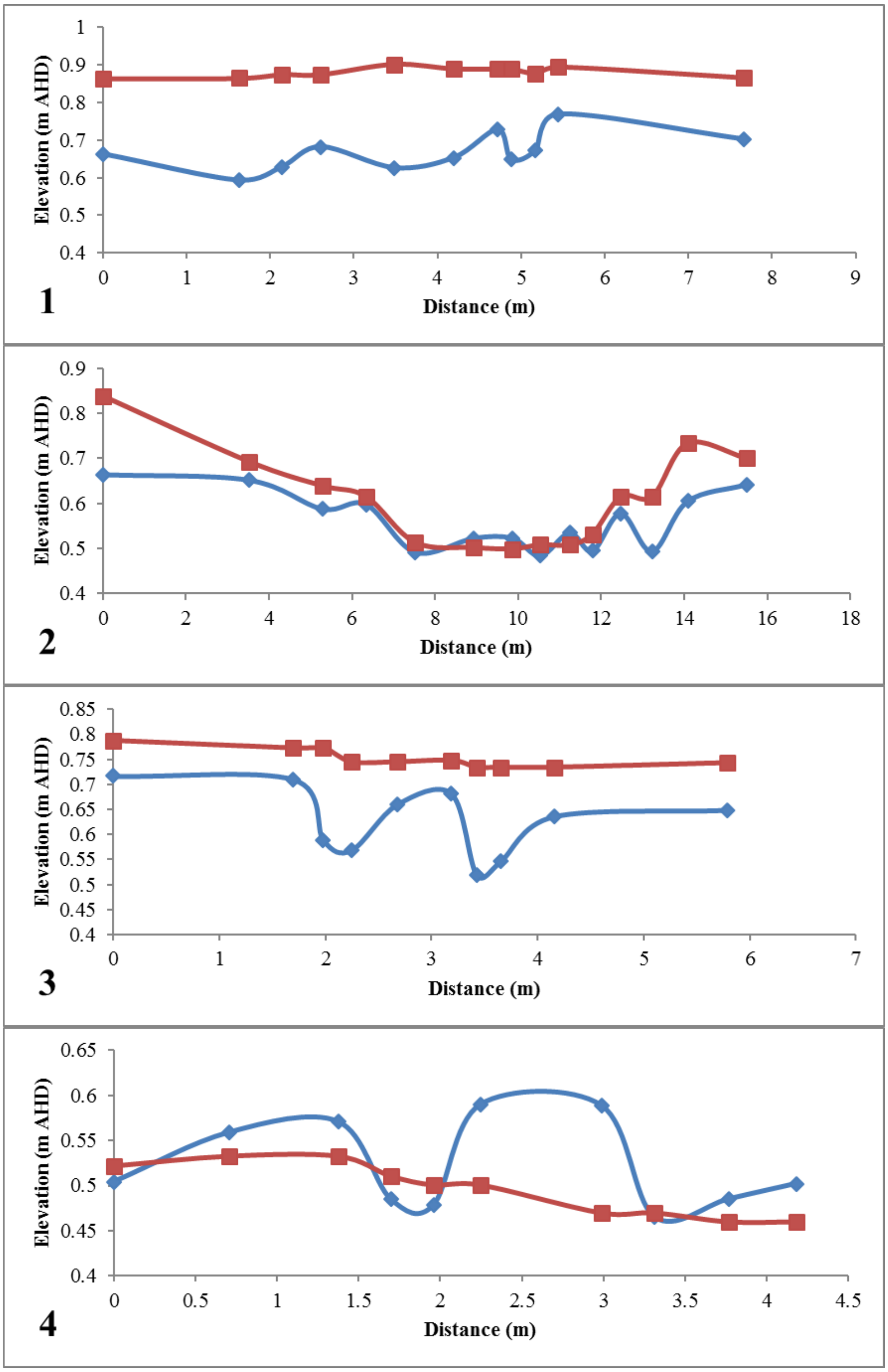

Elevation (m AHD)
Distance (m)
4

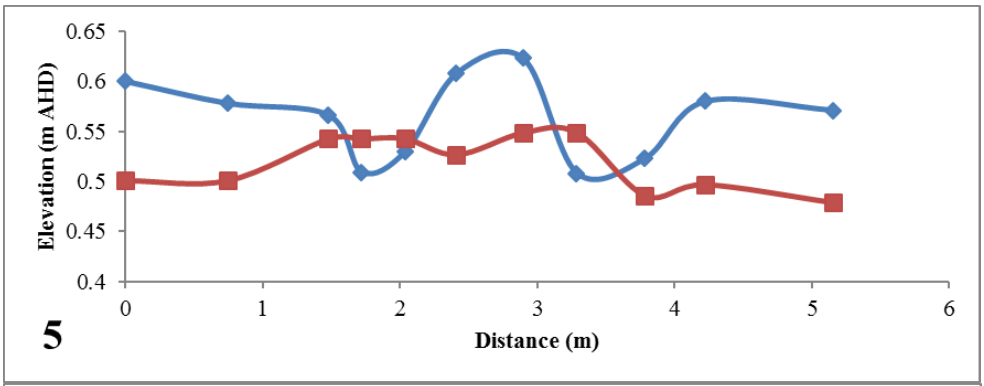

Elevation (m AHD)
Distance (m)
5

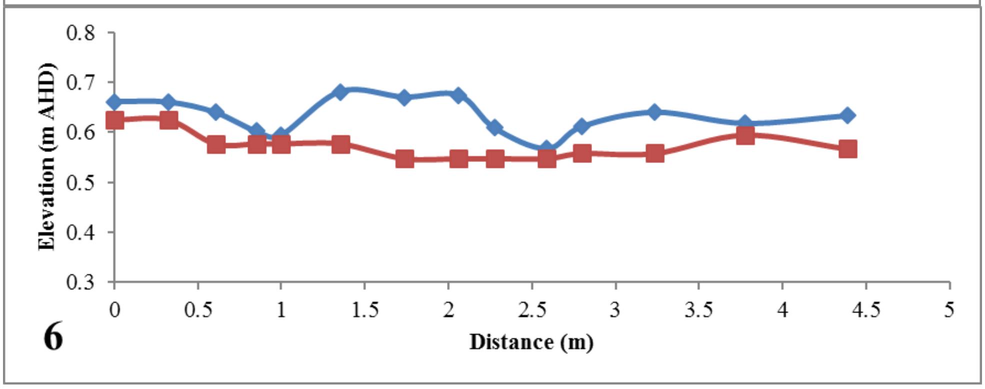

Elevation (m AHD)
Distance (m)
6


Elevation (m AHD)
Distance (m)
7

Tomakin

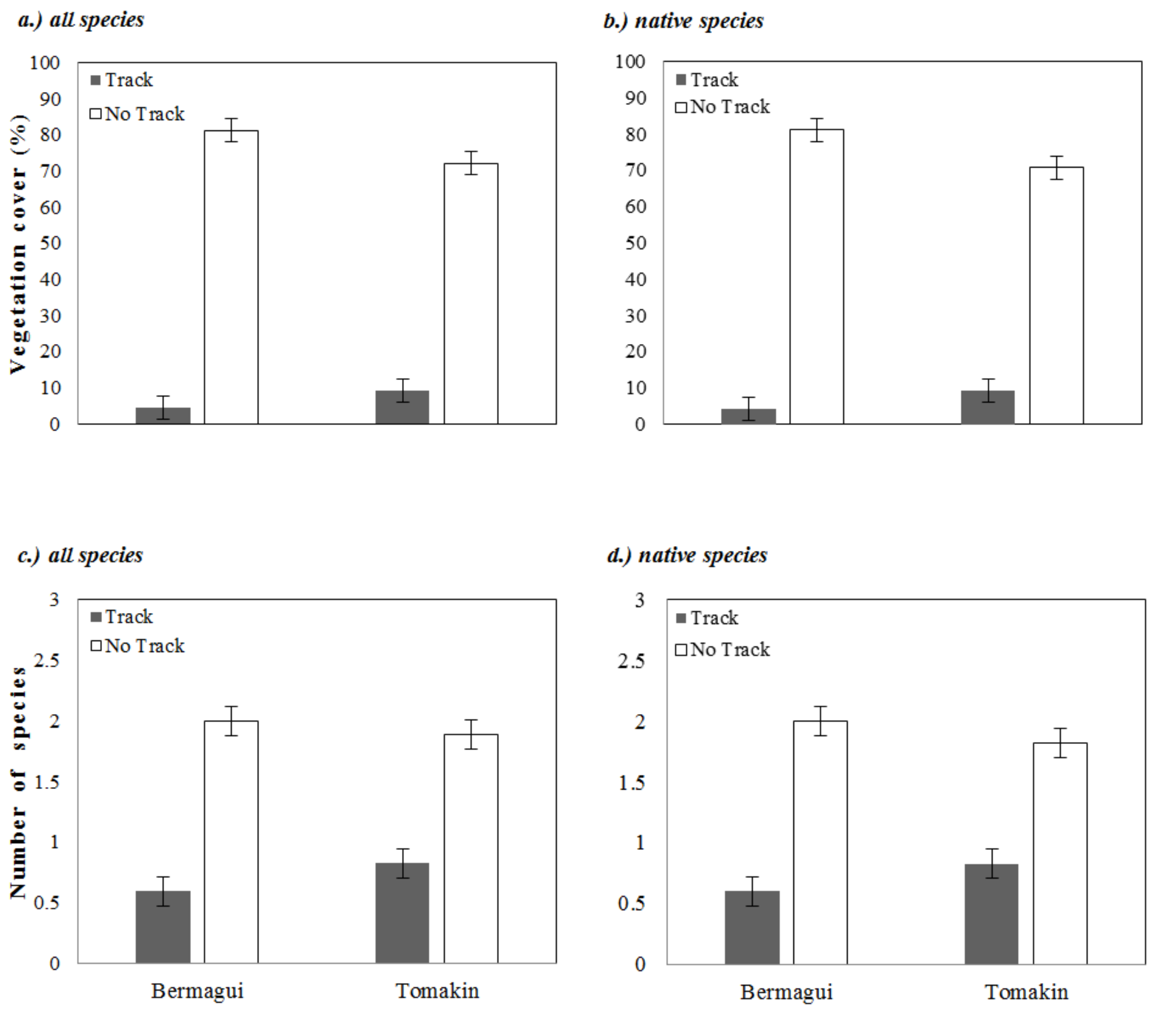



0.65
0.6
0.55
0.5
0.45
0.4
Elevation (m AHD)
0
1
2
3
4
5
6
Distance (m)
5


0.8
0.7
0.6
0.5
0.4
0.3
Elevation (m AHD)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Distance (m)
6

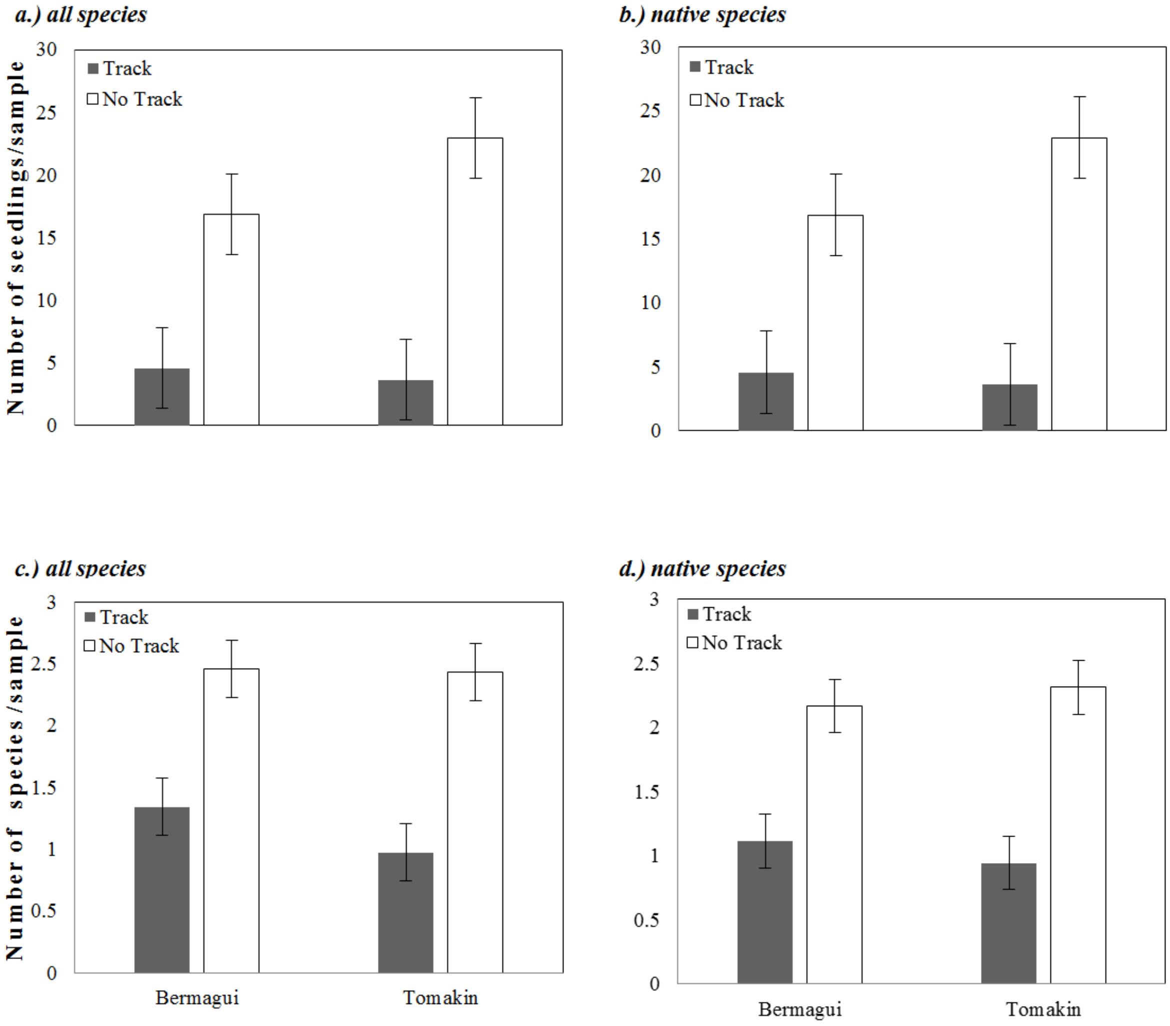
Appendix VI

Mean (±SE) vegetation cover (a) and species richness (b) per quadrat for all species and native species only, within impact (track) and control (no track) areas, at Bermagui and Tomakin



Appendix VII

Mean (±SE) seedling density (a) and species richness (b) per quadrat for all species and native species only, within impact (track) and control (no track) areas, at Bermagui and Tomakin



Appendix VIII

PERMANOVA models of native vegetation species composition for location and vehicle impact (using both abundance and presence/absence data). Bold indicates significant effects (or near significant effects). Pair-wise tests were performed where the interaction effect was significant (or close to), to determine effects within location.

Response variable **Source of variation**	***df***	***SS***	***Psuedo – F***	***P (perm)***
Composition of species in vegetation cover (natives only)				
Abundance				
Location	1	28891	8.8139	**0.001**
Vehicle Impact	1	677727	2.7937	0.47
Location x Vehicle Impact	1	24243	7.3958	**0.001**
Error	238	7.7349×10^5		
Pairwise test ‘Location vs Vehicle Impact’ Within Bermagui			***t***	***p***
Track vs No Track			3.8855	**0.001**
Pairwise test ‘Location vs Vehicle Impact’ Within Tomakin				
Track vs No Track			3.4693	**0.001**
Composition of species in vegetation cover (natives only)				
Presence/absence				
Location	1	24405	9.2518	**0.001**
Vehicle Impact	1	20839	0.6465	0.676
Location x Vehicle Impact	1	32234	12.22	**0.001**
Error	238	6.3046×10^5		
Pairwise test ‘Location vs Vehicle Impact’ Within Bermagui			***t***	***p***
Track vs No Track			3.8987	**0.001**
Pairwise test ‘Location vs Vehicle Impact’ Within Tomakin				
Track vs No Track			1.5543	0.106

SIMPER analysis identifying sources of compositional differences for native vegetation species abundance between impact and control areas. Average dissimilarity values are average Bray-Curtis dissimilarity percentages

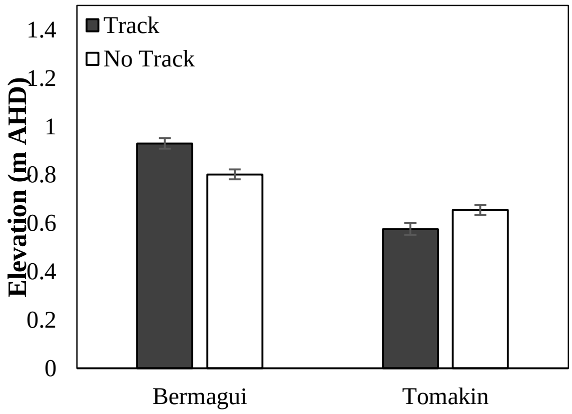
Location	Species	Average abundance		Average dissimilarity	Dissimilarity /SD	Contribution (%)	Cumulative contribution (%)
Bermagui		**Control**	**Impact**				
	S. quinqueflora	15.48	5.32	25.62	0.82	27.82	27.82
	J. kraussii	22.08	0.20	21.69	0.72	23.55	51.36
	S. virginicus	14.49	0.00	14.11	0.56	15.32	66.68
	W. bachhousei	9.89	0.00	10.12	0.38	10.99	77.67
Tomakin							
	S. quinqueflora	28.15	10.19	35.43	1.07	42.55	42.51
	J. kraussii	21.03	1.07	23.15	0.80	27.31	68.64
	A. marina	6.75	2.19	14.53	0.60	17.32	85.66

SIMPER analysis identifying sources of compositional differences for native vegetation species presence/absence between impact and control areas. Average dissimilarity values are average Bray-Curtis dissimilarity percentages.

Location	Species	Average abundance		Average dissimilarity	Dissimilarity/SD	Contribution (%)	Cumulative contribution (%)
Bermagui		**No Track**	**Track**				
	S. australis	0.17	0.60	18.63	1.05	24.45	24.45
	S. quinqueflora	0.40	0.68	17.99	0.99	23.60	48.05
	J. kraussii	0.47	0.04	14.42	0.89	18.93	66.97
	S. virginicus	0.30	0.00	8.70	0.64	11.41	78.38

Appendix IX

Mean (±SE) elevation, within impact (track) and control (no track) areas, at Bermagui and Tomakin



Mean (±SE) elevation, within impact (track) and control (no track) areas, within high and low marsh zones at Bermagui