Hyperspectral Techniques to Detect Off-Road Vehicle Tracks along the Ningaloo Coastline

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This is a declaration that the following thesis, *Hyperspectral Techniques to Determine Off-Road Vehicle Tracks along the Ningaloo Coastline,* for my Environmental Science Masters Project (ENV 600) is the account of my own research and work, apart from the processing of hyperspectral data, which was performed by Dr Halina Kobryn. Otherwise any other references are appropriately acknowledged.

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ABSTRACT

The Ningaloo coastline in the remote northwest of Western Australia has recently emerged as a highly popular tourist destination, attracting thousands of visitors to its coastline to enjoy fishing, camping, snorkeling, wildlife viewing and four-wheel drive activities. In order to protect the unique coastal communities and pristine environment that is responsible for attracting so many tourists, careful planning and monitoring of the coastal roads and access points to beaches is required that minimizes degradation of the natural resources.

In April 2006, hyperspectral sensors captured data over the Ningaloo coastline to map the Ningaloo Marine Park. Hyperspectral remote sensing is a non-invasive tool that can provide information on landforms, vegetation and ground cover that might be missed by other remote sensing tools. Hyperspectral techniques were explored, using Vegetation Indices, Minimum Noise Fraction and Spectral Angler Mapper to detect off-road vehicle tracks in the Ningaloo region. The study covered different management zones, landscapes and ecosystems and certain areas were ground truthed to observe the presence of tracks and their impact on the habitat. Different techniques were more appropriate for identifying tracks over different landscapes; therefore, the combined application of all three approaches extracted the most information on the distribution of tracks.

The derived hyperspectral dataset has the potential to provide an indication of the effectiveness of hyperspectral techniques for monitoring and managing the prevailing network of roads and minor tracks along the Ningaloo coastline. This could assist the Department of Environment and Conservation (DEC) with future assessments of the appropriate level of access and use of the Ningaloo coastal environment and the potential physical impact of vehicular traffic on the vulnerable coastal communities.

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1.1 Australian Coastline

Australia's coastal areas constitute a major part of the national cultural identity and intangible heritage; the beaches provide traditional meeting spots for people to gather and play cricket, beach volleyball and have a BBQ or go fishing with friends. The popularity of Australia's coasts has attracted many people to invest in residential property by the ocean, it has stimulated growth in commercial developments, as well as spurred tourism and associated infrastructure (Schlacher & Thompson, 2008). Coastal management in Australia has an overarching aim to ensure ecological sustainable use of the coast and beaches (Rodney, 2000) so that a balance can be attained between recreational, commercial and environmental interests. This requires the evaluation of socio-economic, aesthetic, recreational and ecological aspects related to land use along the coastline (Rodney, 2000). It also means that development in Australia should employ, preserve, and improve community resources, in a way that safeguards the environment and enriches lifestyles (Rodney, 2000). In short, environmental sustainability is considered inextricably linked to maintaining socially and economically viable coastal communities in Australia (Foster-Smith *et al.,* 2007).

Australia is internationally recognized and acclaimed for its pristine ocean beaches and superb coastlines (Rodney, 2000). Over recent years, this fame has influenced the tourism boom in Australia, boosting the nation's economy by contributing $38,935 billion to GDP in 2006-2007, an increase of 7.8% on 2005-2006, and employing 482,800 persons, a rise of 1.1% on 2005-06 (ABS, 2006). The Commonwealth Government of Australia and the State Government of Western Australia have expressed their deep commitment to ensuring ecologically and economically sustainable development to sustain such tourism success

(Hercock, 1999). However, more information is required on the impact of increasing tourism on Australia's coastal environment (Sun & Walsh, 1998) and the degree to which sustainable tourism is realizable (Hunter, 2002).

1.1.1 Ningaloo Coastline

In Western Australia over 80% of all tourism and recreation occurs in the coastal zone (Priskin, 2003a). The Ningaloo coastline in the remote northwest of Western Australia has recently transformed into a highly popular tourist destination for international, domestic and interstate visitors eager to explore the Ningaloo coastline (Marine Parks and Reserve Authority, 2005). This rise in tourism has injected fresh economy into the community and generated new employment opportunities. This is a welcome relief for the Ningaloo community; when the US Navy withdrew from the area in 1996, the township of Exmouth suffered an overwhelming 25% decrease in population, forcing the community to become solely reliant on the fishing industry and deteriorating pastoral activities (Wood & Glasson, 2005). Today, in order to sustain its newfound economic livelihood, the Ningaloo community needs to effectively manage the pressures from escalating visitations in order to conserve resources and achieve long-lasting benefits from tourism.

The near shore waters, foreshore and coastal hinterland of the Ningaloo coastline offer a superb diversification of recreational opportunities for tourists (MPRA, 2005). Approximately 200,000 people visited Ningaloo in 2004, partaking in a range of coastal activities including wildlife viewing, boating, fishing, diving, snorkeling, camping, touring and four wheel-driving (Western Australian Planning Commission, 2004). People's entitlement to access the beach and foreshores is naturally presumed by tourists (Kay *et al.*,

1997) and to support rising visitations and associated expectations, accommodation and tourist operators have expanded.

However, to achieve sustainable tourism, better planned access to coastal areas is required, for, although recreation in coastal areas is distributed over a vast area, significant degradation of coastal nodes has occurred at locations of high human intensity (WAPC, 2004). Degradation is the result of littering, trampling of vulnerable habitat, insensitive disposal of human waste and damage to coastal environments by four-wheel drive and other off-road vehicles. Remote natural areas are particularly susceptible to the impacts of four-wheel drive recreation, creating complex coastal management issues (Priskin, 2003a). As visitor numbers rise, there is fear of increasing environmental destruction, particularly on the more popular foreshore nodes or adjacent to marine access points (MPRA, 2005).

a b c

Figure 1 a) Easy access to rocky shorelines for fishing attracts tourists to the coasts. b) Tantabiddi boat ramp has become crowed with tourists fishing and whale watching. c) Field observations showed that campsites are often full during peak seasons.

1.2 Off-road vehicle use along Australian Coastline

Over recent years, Australia has witnessed a significant increase in the sales and usage of four-wheel drive vehicles and similar transport with off-road capabilities, such as Sports Utility Vehicles (SUVs). They have become progressively more readily available and affordable (Stephenson, 1999) to meet growing demands from adventurous customers, including tourists and a younger retiree market, who desire to tackle mud, sand, gravel and water areas where standard vehicles fail to access (Taylor, 2001). A record of 1,049,982 vehicles (truck, standard cars, etc.) was sold in Australia in 2007, which marked a 9.1% increase over 2006. Of the additional 87,000 sales, 27,329 were SUVs and 15,052 were 4x4 pick-ups, comprising a major proportion of the overall market growth (Federal Chamber of Automotive Industries, 2008). Therefore, as seen, the sales and hiring of off-road vehicles for recreation can generate large economic benefits.

Leisure activities along coastal areas frequently involve the use of off-road vehicles being driven over beaches and sand dune systems. For many years their detrimental long-term affect on coastal habitats, organisms and ecosystems has been a controversial issue in Australia and throughout the world (Godfrey & Godfrey, 1980). As early as the 1970's, the impact of off-road vehicles on Australian coastlines was recognized by the Government as causing disturbance to wildlife and damage of wilderness, including loss of vegetation resulting in soil erosion (House of Representatives, 1977). Similarly, Australian ecologists and environmental groups have been alarmed by the potential impact of off-road vehicles on sensitive ecosystems. Sadly, although the ecological attributes of beaches and dunes are publicly less known compared to their social and economic aspects, their disappearance risks creating catastrophic and irreversible consequences to vital ecosystem functions, biodiversity, and habitat (Godfrey & Godfrey, 1980). The significance of recognizing the valuable worth of our natural resources is reiterated by the following author Cairncross in his publication, *Costing the Earth*:

> In a world where money talks, the environment needs value to give it a voice (Cairncross, 1991).

1.2.1 Off-road vehicle use along Ningaloo's Coastline

Vehicle traffic numbers passing through the Cape Range National Park from the north to Tanatabiddi, increased from 13,940 during 1989-1990, to 30,144 during 1998-1990. This marked a rise of 42,000 to 84,000 visitations (WAPC, 2004). Similarly, Ningaloo's Minilya - Exmouth Road reported a daily average of 200 vehicles from 1998 to 1999, which marked a 3.8% annual increase compared to traffic flow from 1989 to 1990 (WAPC, 2004). The intensification of traffic is causing greater pressure on the existing coastal access network and some areas can no longer support the increased usage. Not satisfied with traditional access areas, people often use off-road vehicles to traverse past the supervised zones and look for more remote locations (Taylor, 2001). The presence of four-wheel drive vehicles is shown in Figure 2.

Insufficient track management, risks prompting indiscriminate access to new spots along the coast, as well as the chaotic spread of camping, fishing and snorkeling sites in inappropriate settings. The unplanned expansion of additional tracks and low standard of roads could cause even more detrimental impacts on the environment (WAPC, 2004). A strategy to organise sustainable tourism coastal development, and guide integrated land use and transport planning along Ningaloo coast has been undertaken through the *Ningaloo Coast Regional*

Strategy Carnarvon to Emouth (WAPC, 2004). It aims to ensure that land use function drives the transport and not vice versa (WAPC, 2004).

a b c

Figure 2 a) Four-wheel drive vehicles drive through Cape Range. b) Four-wheel drive vehicle at Yardie Creek on the beach and c) tracks on the beach at Yardie Creek from off-road vehicles.

Primary Aim of Study

The primary aim of this study is to analyse the distribution of off-road vehicle tracks along the Ningaloo coastline to assist the *Ningaloo Coast Regional Strategy Carnarvon to Exmouth* with future assessments of the appropriate level of access and use of the Ningaloo coastal environment. Secondary aims and methods will be mentioned on p 15.

2 Off-road vehicle impact on Ningaloo's coastal communities

2.1 Dune systems

Sand dunes function as a shield, blocking storm winds and waves from washing sea water over houses, roads and recreational facilities constructed behind the dunes (MPRA, 2005).

Vegetation is vital for the formation and stabilization of sand dunes. Research has shown that vehicle traffic over dunes decreases both the total cover and height of vegetation (Rickard *et al.*, 1994). The destruction of stabilizing vegetation allows aeolian activity to reduce the dune height, cause erosion blowouts and ultimately decrease the ability of the dune system to endure storm winds and waves (Priskin, 2003b). Intense, continued use of a single path over a dune can result in lowering of the dune crests, ultimately causing the dune to split and significantly altering the dune topography (Rickard *et al.*, 1994). This is observed in Figure 3.

Figure 3 Evidence of track making within Cape Range National Park in the foredunes and through coastal blowouts.

Ningaloo's coastal biological communities are characterized by fragile Holocene dunal habitats, hard coastal limestone platform and arid perennial shrubs. The main types are represented by *Acacia, Eremophila, Cassia, Atriplex, Triodia* and *Eucalyptus* (Bancroft & Lapwood, 1999). This coastal ecosystem plays a valuable role in protecting dunes from erosion (MPRA, 2005). Hardy plants in the foredune and primary dunes can usually withstand natural types of biological and physical harm, including fire, high speed winds, sand blasts, salinity and drought (MPRA, 2005). However, trees and shrubs are the least resilient and suffer widespread degradation from the impact of off-road vehicles (Groom *et al.*, 2007). Ultimately continuous traffic flow prevents dune re-vegetation (Van der Merwe, 1988).

Management of the Ningaloo coast is shared between the adjacent pastoral land owners and the Department of Environment and Conservation (DEC), to facilitate access for visitors to and along the coast (WAPC, 2004). However, despite the management strategies employed by pastoral stations, considerable degradation of the delicate environment, particularly coastal vegetation, has led to erosion and remobilization of sediment (WAPC, 2004). Environmental degradation is linked to the uncontrolled development of access roads, leading to the proliferation of networks of tracks (Blackwell, 2002). Further insufficient management of four-wheel drive vehicle access, along Ningaloo could cause the erosion of the fore-dune system (MPRA, 2005). Consolidation and supervision of access tracks and camping grounds is necessary to reduce the damage to coastal communities and allow degraded areas to recover (MPRA, 2005). If not managed, tracks will increase in density, and continue to spread out from inland access points towards the coast (Priskin, 2003).

2.2 Beaches and salt marsh communities

International studies carried out on Fire Island National Seashore, USA, have reported that vehicle passage along sandy beaches causes sand accumulation in the backshore zone and erosion in the intertidal zone (Godfrey *et al*., 1978). Vehicle traffic over beaches smashes the salt crust and pulverizes and disperses organic matter as winds and swash activity sweep the sediment away from the beach. The churned up sand dries out, losing its nutrients and crushed seeds are unable to colonise the dune areas (Godfrey *et al*., 1978). Depending on the tyre width, vehicles can penetrate as deep as 20 cm and increase the rate of beach erosion by up to 25% (Godfrey *et al*., 1978). By displacing large volumes of sand, causing compaction and rutting of the sand matrix with tyre tracks (Anders & Leatherman, 1987), off-road vehicles can destroy the plants regenerating below the sand surface (Godfrey *et al*., 1978) and significantly reduce the variety and survival of organic content and biodiversity, including turtles and shorebirds (Schlacher *et al*., 2000b).

Beaches contain diverse, dynamic and sensitive ecosystems (Beatley, Brower, & Schwab, 2002 cited in Schlacher *et al.*, 2008c). A single beach can harbour several hundred species of invertebrates such as the interstitial micro - and meiofauna (Armonies & Reise, 2000 cited in Schlacher *et al.*, 2008c). Beaches offer unique ecological services, such as filtration of extensive volumes of seawater, (Brown & McLachlan, 2002), nutrient recycling (Kotwicki *et al*., 2005) and provide critical habitats for feeding, breeding and foraging grounds for endangered species such as turtles (nesting) and shorebirds (roosting) (Rumbold *et al.*, 2001). Viewing beaches as simply mounds of sand lacking life places in jeopardy the enormous ecological value of sandy beaches (Brown & McLachlan , 2002).

The beach habitat (sublittoral sand) of Ningaloo consists of carbonate sand, covering limestone surface (Cassata & Collins, 2008). The beach is mostly unvegetated, however, flora such as spinifex *(Spinifex longifolius)* may exist. Ghost crabs *(Ocypode sp.),* as well as a range of invertebrates including bivalve shells and sea urchins *(Diadema sp.)* may also be present (Brancoft & Sheridan, 2000). The salt marsh habitat is located along the intertidal and supratidal shore of low energy coastlines, consisting of muddy or silty terrigenous sediment (Brancoft & Sheridan, 2000). The salt marsh community contains salt-tolerant plants and low shrubs mixed with bare salt flats, as well as ghost crabs, insects, worms, invertebrate larvae, and bacteria. This habitat also supplies food for birds and fish and provides a nursery ground for large fish larvae (Cassata & Collins, 2008).

Along many areas of the Ningaloo coastline, visitors can view or be in very close proximity to the ocean while travelling along the coastal roads and this also accelerates uncontrolled access to the beach (WAPC, 1996). It is also a challenge to direct visitors to appropriate spots as long stretches of coastline are easily reachable by many tourists (WAPC, 1996). Large areas outside the park, such as south of Yardie Creek rely generally on the common sense and good intentions of those camping and travelling along the coastal road (WAPC, 1996).

2.3 Mangrove coastal swamps and intertidal mudflats

Ningaloo's mangal habitat, such as Mangrove Sanctuary and Yardie Creek that are depicted in Figure 4, contain the common *Avicennica marina*, *Rhizophora stylosa,* and *Bruguiera exaristata* mangroves. They typically grow in the upper intertidal zone on essentially muddy, silty clay substrate (Cassata & Collins, 2008). The mangrove roots provide substrata for various gastropods (e.g. *Natica*, *Cerithium*, *Stombus*) and mangrove crabs *(Scylla serrata)* (Brancoft & Sheridan, 2000). Burrowing worms, and insects also inhabit the area and the mangal habitat provides refuge for the juveniles of various fish species (Cassata & Collins, 2008).

a

b

Figure 4 a) Mangal habitat at Yardie Creek b) and at Mangrove Sanctuary.

The mudflat habitat located in parts of Ningaloo, such as Bundegi Coastal Park is found along the lower intertidal zone, often seawards from the mangal habitat, typically displaying a flat, rocky limestone platform covered by a surface of silty, fine sand (Cassata & Collins, 2008). Covered with a veneer of microorganisms, these areas offer essential nutrients for many invertebrate species (MPRA, 2005). The high diversity of invertebrates living within the mudflat sediment provides vital feeding grounds for teeming resident and migratory shorebirds (MPRA, 2005). Crabs, small bivalves (*Mytilus*) and other infaunal benthic invertebrates (Cassata & Collins, 2008) also rely on the mangal habitat as an important food source. Localized disturbance from trampling and vehicle access has occurred in these areas, as shown in Figure 5, where mangroves are associated with recreational nodes and activities such as mudcrabbing (MPRA, 2005).

Figure 5 Tracks observed while ground truthing areas of mudflats nearby Bundegi Coastal Park

2.4 Arid soils

The force of rolling wheels on arid soil can cause soil compaction, which decreases water infiltration and increases runoff, resulting in severe erosion (Webb, 1983). Soil stabilizers include macrofloral elements (plants), microfloral elements (lichen, fungal, and algal crusts) and inorganic elements (soil crusts) (Webb, 1983). When these stabilizing plants are crushed, the susceptibility to wind and water erosion increases, which accelerates decomposition of organic matter, weakens soil stability, and causes inorganic surface crusts. These surface crusts increase runoff, inhibit the germination and emergence of seedlings, and reduce water penetration, resulting in a harsher environment for plants and animals to survive (Dregne, 1983). The degree of loss is dependent on the intensity of use and may vary from site to site. Smaller shrubs are often the first to be damaged or eliminated (Taylor, 2001).

Figure 6 Track over semi-arid soil 1km south of Yardie Creek

Off-road vehicles can also spread invasive or noxious plants (Taylor, 2001). Nonnative plant invasion is evident along the Ningaloo coastline, particularly buffel grass invasion, which is partly the result of disturbance from track making and unregulated camping.

Figure 7 Buffel grass invasion at near Mandu Mandu in Cape Range National Park

2.5 Off-road vehicle impact on wildlife

A study by Havlick (2002) showed that wildlife such as birds, small mammals and reptiles react to four-wheel drive vehicle commotion with increased heart rate and metabolic activity, and suffer abnormally high levels of stress, resulting in mortality and reproductive malfunction. This disturbance tends to force wildlife to avoid areas, thus interrupting their breeding and feeding patterns. Havlick’s investigations also found that noise from four-wheel drive vehicles and especially dune buggies can severely damage the senses of wildlife, harming their ability to protect themselves against predators and source prey. Similarly, Brattstrom and Bondello (1983), discovered that the acoustical sound of dune buggies caused loss of hearing in the Mojave fringe-toed lizard even over limited time. Beach buggies are considered to inflict even more damage on sand dune systems than four-wheel drive vehicles due to the limited traction of their rear-wheel tyres, which creates a lot of spin in the sand and excessive sediment displacement (Brattstrom & Bondello, 1983) Along the Ningaloo coastline the detrimental effect of buggies on dune systems and the associated wildlife does not appear to be recognised. Advertised in the Tourist Exmouth Office is the following information on flyers to attract tourists to partake in buggie wildlife tours near Coral Bay:

> *Beaches, bushtracks, pristine bays, dunes, clifflines, abundant wildlife ... make this an exciting way to discover the spectacular and isolated coastline of Coral Bay. See turtles feeding ...and experience the raw beauty of our unique coastline all with you at the controls of our modern and well maintained, specially designed two-seater quad bikes ... No experience required... (Coastal Adventure Tours, Exmouth).*

A total of 144 bird species has been recorded on North West Cape, of which one-third are seabird, shorebirds and waders, both resident and migratory (May *et al.*, 1983). There are approximately 33 species of seabirds found in the Park, 13 of which are resident and the other 20 are migratory birds or occasional visitors (DEC, 2002). The main rookeries in the Ningaloo Marine Park are found at Mangrove Bay, Mangrove Point, Point Maud, the Mildura wreck site and Fraser Island (MPRA, 2005). Outside the park, other places such as Winderabandi Point are also important bird rookeries. Levels of the use of the coast in the reserves vary considerably. In terms of recreational vehicle and four-wheel drive usage, there is a high level of use around Coral Bay and Point Billy (adjacent to Ningaloo Station) and low use adjacent to Cape Range National Park where driving on the beach is prohibited. Given this diversification of usage and the associated management strategies to control such use, no current major pressures on seabirds, shorebirds and migratory waders in the reserves have been recorded (MPRA, 2005). However, there is discussion for the implementation of spatial controls to offer protection to seabird nesting and roosting areas and increase education and awareness with shoreline users (MPRA, 2005).

Green turtles *(Chelonia mydas)*, loggerhead turtles *(Caretta caretta)* and hawksbill turtles (*Eretmochelys imbricata*) inhabit the Ningaloo region, including Gnaraloo Bay for nesting (MPRA, 2005). One of the most significant threats faced by the turtles is the increasing pressures from rapidly growing tourism to the region, which is significantly interfering with turtle nesting along the beaches (MPRA, 2005). Turtles are sensitive to light and movement. Vehicle track making and unregulated camping by visitors, means that turtles are frequently disturbed during nesting, resulting in them abandoning the nest and escaping to the ocean (Hosier *et al*., 1981). The light pollution emitted by car headlights traversing along tracks or from car parks can also disturb nesting turtles and disorientate emerging hatchlings (Hosier *et al.*, 1981).

Careful consideration of the present road network along Ningaloo's coastline is required, as well as attention to planning of building new coastal roads, which is sensitive to the exposure, these precious coastline communities will endure from the available access routes and subsequent increased visitation.

Secondary Aim of Study

To assist with road strategy, this study aims to analyse different hyperspectral remote sensing techniques for the presence and distribution of tracks along Ningaloo's coastline to assess their effectiveness as a monitoring tool for management. Selected areas of Ningaloo's coastline will be studied using hyperspectral imaging, complimented with field observations to explore and evaluate the use of hyperspectral techniques for mapping tracks in semi-arid environments. An exploration of these techniques will be carried out to evaluate their effectiveness in identifying tracks along Ningaloo's coastline.

3 Hyperspectral Remote Sensing

3.1 Hyperspectral Imaging

Hyperspectral imaging measures the variations in wavelength from the radiation reflected absorbed or emitted from any material on the Earth's surface (Manolakis *et al.*, 2003). To capture the discrete variations in radiation, hyperspectral-imaging sensors are equipped with hundreds of narrow bands, which make them more effective than the traditional broad, band multispectral sensors, such as Landsat TM (Cocks *et al.*, 1998). Hyperspectral sensors have a unique capability to continuously collect spectral information across a wide range of wavelength bands (Manolakis *et al.*, 2003), which is illustrated in Figure 8. For example, hyperspectral data can characterize certain plant properties such as, chlorophyll by identifying their distinct spectral signature.

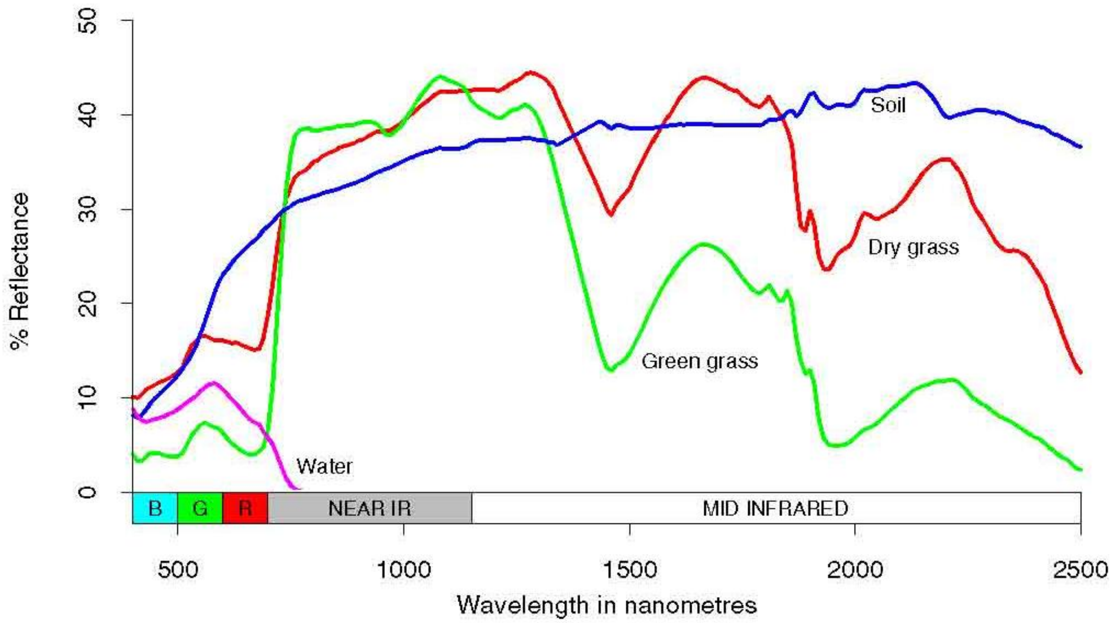


Figure 8 Different materials produce various electromagnetic radiation spectra, as displayed in this graph of reflectance of soil, dry grass, water and green vegetation. The spectral information contained in a hyperspectral image pixel can therefore indicate the range of materials present in a scene (Lillesand & Kiefer, 2000).

Another distinct advantage of hyperspectral imaging to other remote sensing techniques, such as colour aerial photography, is that the image is undamaged by sun glint due to the sensor's ability to scan lines perpendicular to the flight direction (Hill & Mégier, 1994). In addition, unlike colour aerial photography, where the spectral separation is poor, hyperspectral imagery processing is fast and automatic; data can be captured in varying weather conditions due to its ability to correct atmospheric effects; and the availability of spectral libraries in the classification means less fieldwork is required (HyVista, 2006). In addition, like many remote sensing techniques, the hyperspectral sensor can map large areas rapidly that would otherwise be difficult to access on foot and more costly to survey on the ground (Manolakis *et al*., 2003).

The airborne hyperspectral sensor HyMap contains 128 bands with almost contiguous spectral coverage across the wavelength interval of 0.44 – 2.5 um and two thermal bands. This design has improved operational stability, calibration accuracy (spectral and radiometric) and it has excelled in terms of high signal to noise ratio performance, band to band registration (0.1 pixels) and image quality (Cocks *et al.,* 1998). By detecting characteristic absorption features of material, HyMaps can be used for various terrestrial applications, including environmental monitoring, agriculture, forest regeneration, mapping geological cover, soil degradation, assessing vegetation condition, including native or invasive vegetation cover or evaluating habitat loss (Cocks *et al.,* 1998).

3.2 Hyperspectral vegetation discrimination in semi-arid environments

The Ningaloo coastline is located between arid, temperate and tropical provinces (MPRA, 2005). In order to both identify and classify sand, clay and limestone tracks within this type of environment, a remote sensing approach is required that can best discriminate between dry vegetation and bare areas, and tracks within the landscape. In arid ecosystems, vegetation cover and condition commonly fluctuate due to large variations in land use and climate (Asner *et al.,* 2000). These changes in dry plant material, leaf litter and bare soils display only discrete variability in the reflectance of their spectral properties in the shortwave spectra (Asner *et al.,* 2000). Therefore, to monitor semi-arid environments, it can be difficult to discriminate such reflectance with broad, band multispectral remote sensing (Hill & Mégier, 1994).

Hyperspectral remote sensing provides a promising alternative for the characterisation of foliage and bare soils (O'Kin *et al.,* 2000). However, applying spectral indices alone, such as the normalized difference vegetation index (NDVI), rarely succeeds in detecting all significant biophysical properties of a semi-arid ecosystem, particularly after regeneration (O'Kin *et al.*, 2000). Rather, by combining the automated spectral mixing approach of hyperspectral imagery, using the continuous shortwave spectrum (0.4 µm to 2.5 µm), quantitative estimates for landscape classes can be achieved, as well as assessments of qualitative material (Hill & Mégier, 1994).

In light of the literature findings on the use of hyperspectral techniques in a semi-arid environment, this study applied a combination of interpretation approaches to best detect tracks, along Ningaloo's coastline.

4 Methods

4.1 Study Areas

A variety of study areas were chosen for this study, representing different landforms, habitats and management strategies with the aim of comparing the distribution of tracks within these different areas.

4.1.1 Ningaloo region

The Ningaloo region contains a diversity of land systems of significant physical and biological conservation value, which are shown in Figure 9. The Cape Range district rises 300 m above sea level and contains deeply dissected limestone ranges, sand and coastal plains and outwash alluvial plains, which receive run-off from the plateau (WAPC, 1996). The Cape Range is vegetated with *Eucalyptus* over *Triodia* with *Acacia* shrubs. The coastal plain is predominately vegetated with grasslands, coastal strand vegetation, low shrublands (including Samphires and Saltbush) and Mangrove low forest and the sandy plain by heath and *Triodia* (Keighery & Gibson, 1993). The Ningaloo Reef is one of the largest fringing reef systems in the world. Stretching over 300 km long, the reef is renowned for its unique oceanography, marine wildlife, climate and geomorphology (DEC, 2002).

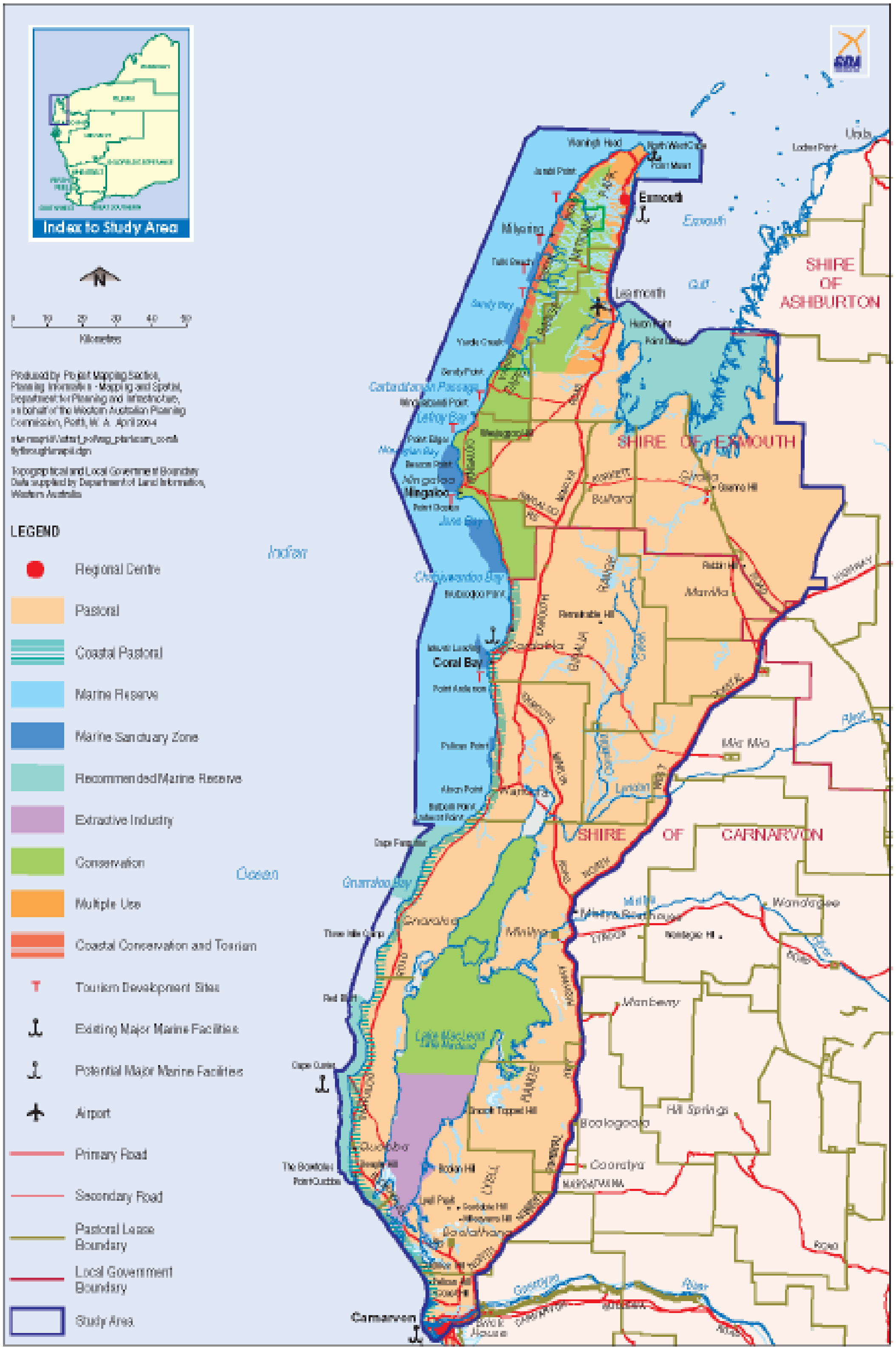


Figure 9 Location of study areas in relation to the Ningaloo Marine Park and Cape Range National Park from (WAPC, 2004).

4.1.2 Gnaraloo Bay

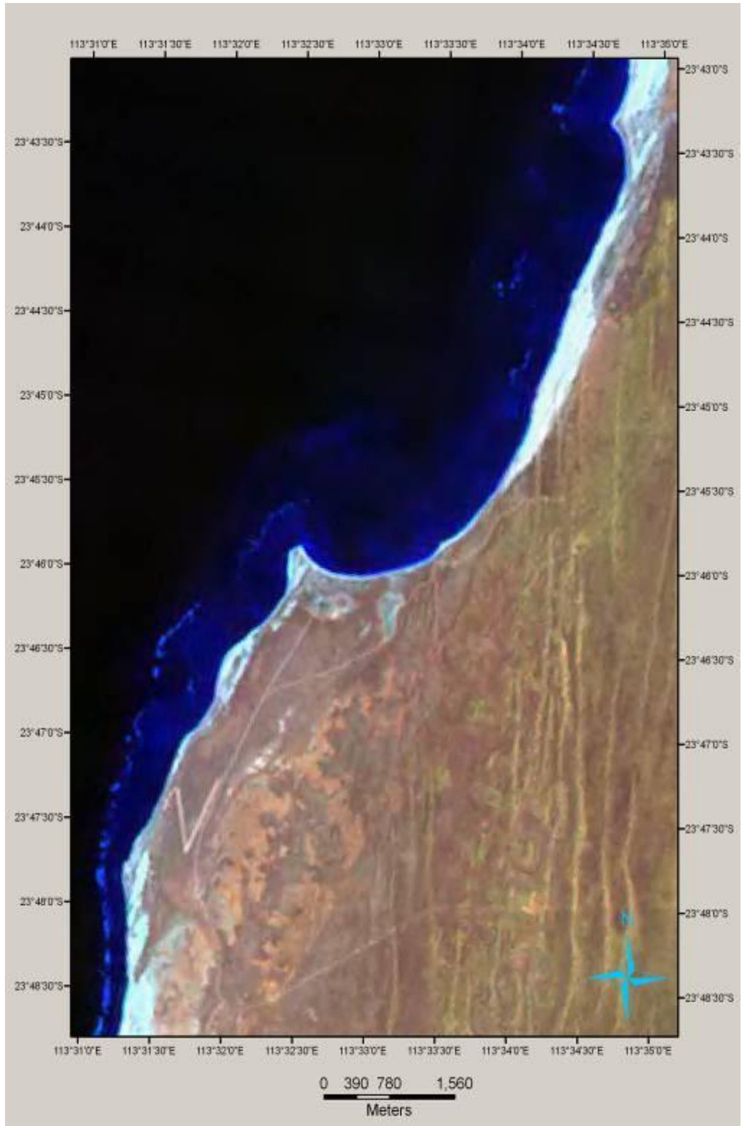


Figure 10 High resolution, aerial imagery over Gnaraloo Bay, Area A on Fig. 16.

Gnaraloo Bay (Figure 10) is located on a fragile coastal dune system, which includes mobile dunes, rocky platforms and limestone cliffs, as well as a cuspate spit (WAPC, 2004). The dominant local vegetation is pindan (Keighery & Gibson, 1993) and the adjacent waters are part of the proposed extension of the marine park, containing a variety of marine habitats. East of the sandy point are important turtle rookeries (Keighery & Gibson, 1993). The area has been under pastoral lease; however, like many coastal pastoral leases, the lease is due to expire in 2010 and come under management by the Department of Environment and Conservation (DEC, 2002).

Currently, supervised campsites and station accommodation is available. It has been recommended as a potential tourism node for eco-lodge development and boat launching, vista platforms, walking tracks and nature exploration activities (WAPC, 2004). There are numerous tracks and roads crisscrossing through the area, which is evidence of pastoral land uses. The publicly accessible road to and from Carnarvon stops at Gnaraloo Bay and the track north is gated and closed (DEC, 2002). The dunes and beach are fragile and unsuited to any development. The Point Quobba to Gnaraloo road is an unsealed two lane track providing access to Gnaraloo Bay. Two wheel drive access terminates at Gnaraloo Station (WAPC, 1996).

4.1.3 Winderabandi Point

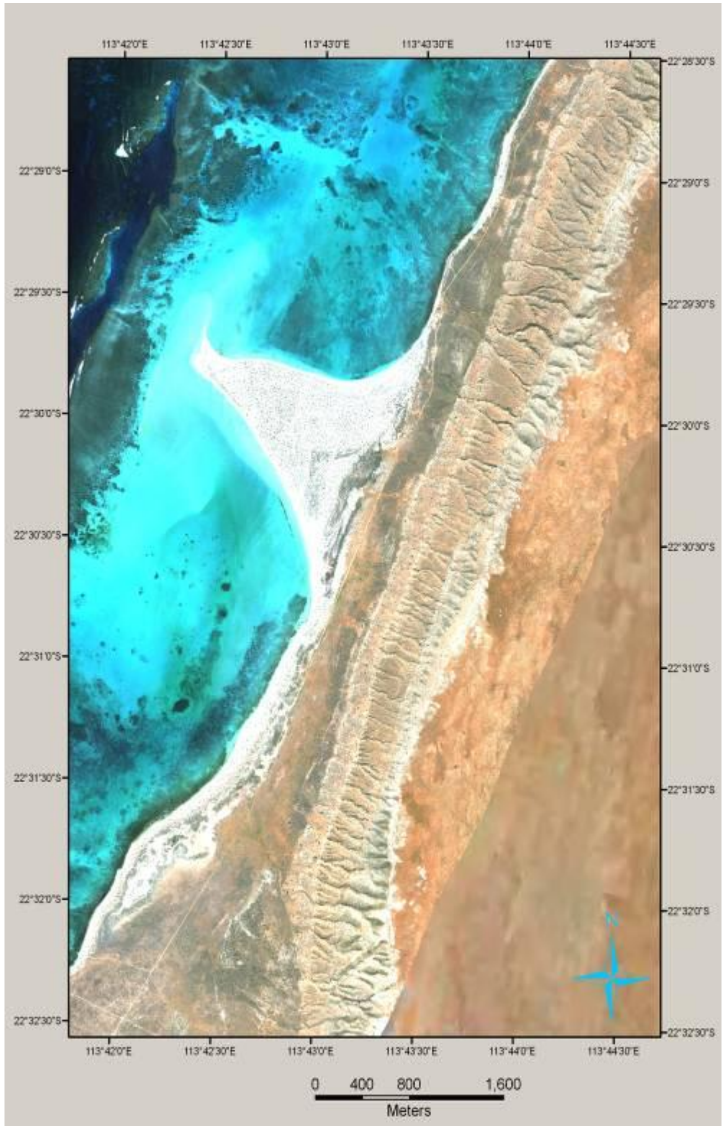


Figure 11 High resolution, aerial imagery over Winderabandi Point, Area G on Fig. 16.

Winderabandi Point (Figure 11) is located on a coastal dune system and cuspate spit in a semi-remote area within the Cape Range. Local vegetation is described as sparse shrub steppe. The waters adjacent to the node contain habitats of sand, shoreline reefs, subtidal reefs, and subtidal and intertidal coral reefs, and are within the Ningaloo Marine Park (MPRA, 2005). Bird roosts of seabirds (*Sterna caspia*, *bergii*, *dougallii*, *nereis*, *Esacus neglectus*, *Phalacrocorax varius*, *Pandion haliaetus* and *Haliaetus leucogaster*), (DEC, 2002) shorebirds and migratory waders protected by RAMSAR Convention are situated on the edge of Winderabandi Point (WAPC, 1996). South of the point is a recreation zone.

The area will be affected by the pastoral lease exclusion process and there is also a mining lease over the area. Poorly defined tracks, campsites and toileting areas have significantly disturbed the fragile dune landforms, swales and vegetation composition (WAPC, 2004). The area has been identified for a potential eco-lodge complex and camping development as it has great tourist appeal, however, if the node is left ill-defined and unmanaged it would become seriously degraded. Unsupervised camping and day use activities have resulted in significant and accelerating loss of native vegetation and erosion of fragile dune systems (DEC, 2002).

4.1.4 Yardie Creek

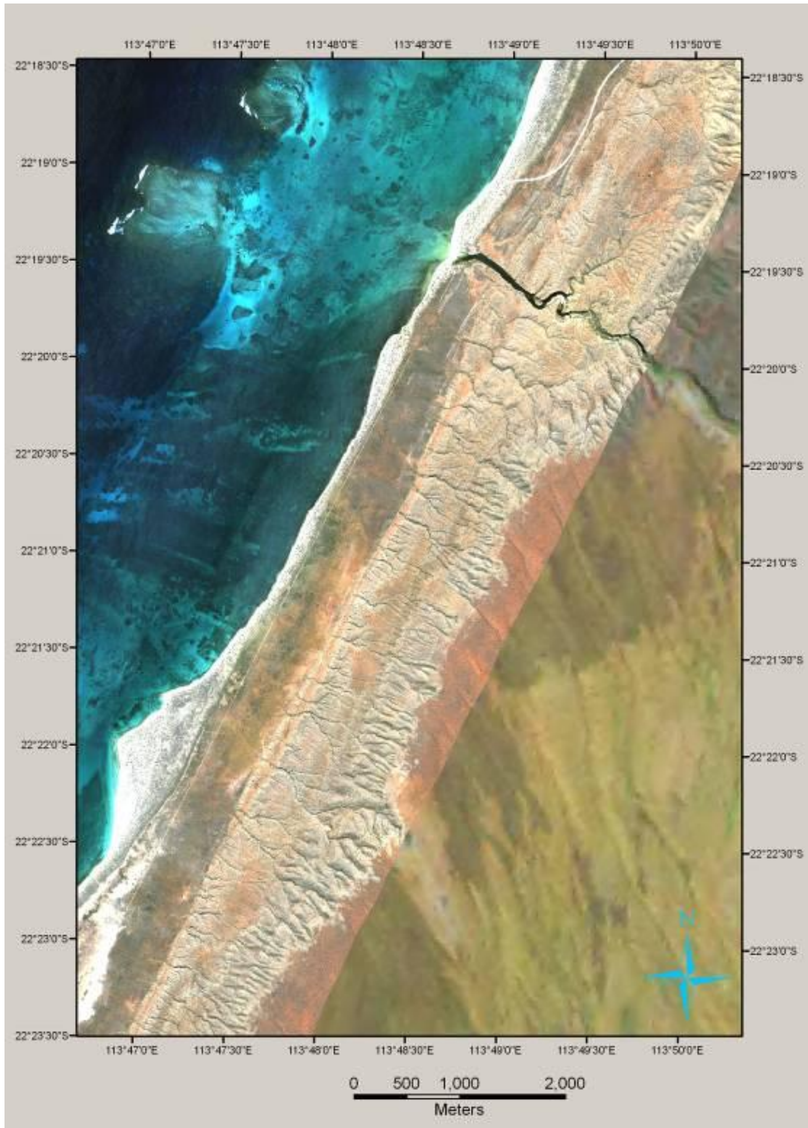


Figure 12 High resolution, aerial imagery over Yardie Creek, Area G on Fig. 16.

The coastal landforms around Yardie Creek (Figure 12) comprise large dunes, sand plains and salt flats adjacent to Cape Range (Keighery & Gibson, 1993). Cliffs, narrow beaches and mobile sand drifts also feature in the dunal landforms where soils vary from deep calcareous sands along the coast to siliceous sands (WAPC, 1996). Currently, under pastoral lease, the area is also a part of the Ningaloo Marine Park and is included as a portion of the Cape Range National Park (WAPC, 1996).

Being a popular destination for campers and fishermen, there are various uncontrolled and unsupervised camping sites south of Yardie Creek, which has placed the area under increasing recreational pressure (WAPC, 1996). The Ningaloo access road is an unsealed road linking Ningaloo Homestead and Learmonth-Minilya Road. It also provides unsealed, two-wheel drive access to Yardie Creek. Further minor roads diverge off this road and fan out in the direction of the beach (WAPC, 2004). It is currently recognised as a potential tourism node for development; therefore further off-road vehicle management may be required in the future.

4.1.5 Mangrove Sanctuary

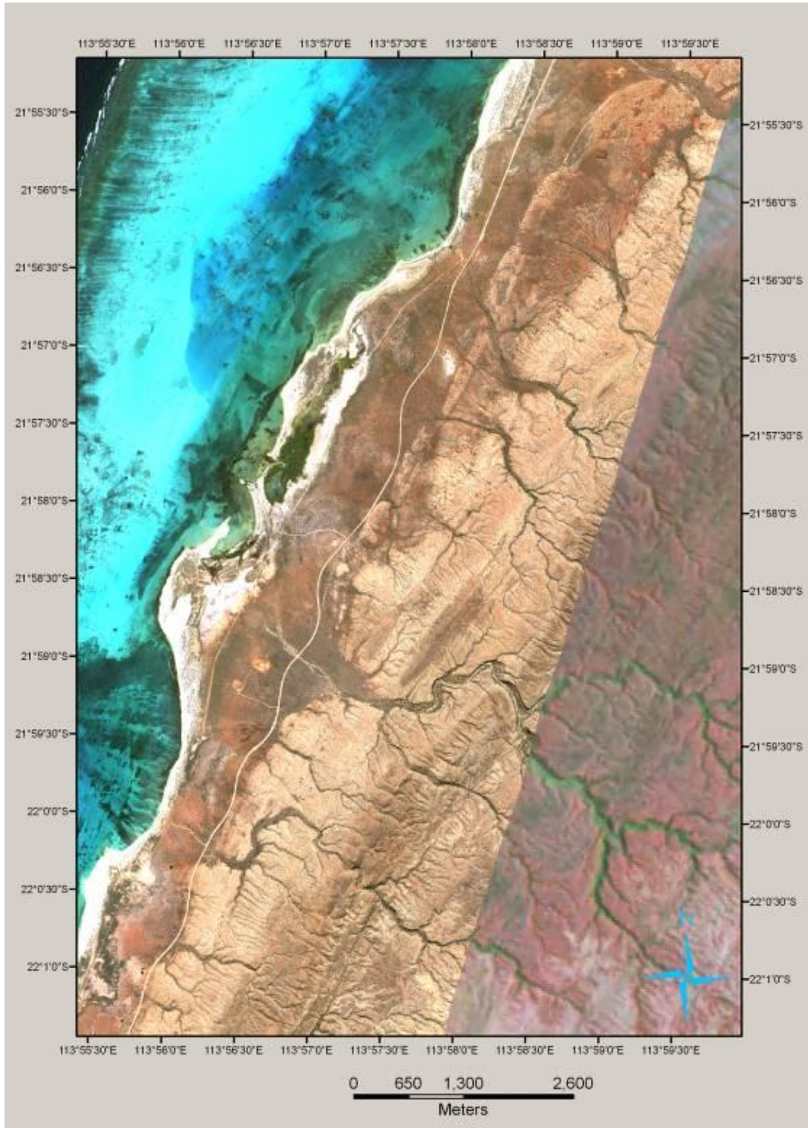


Figure 13 High resolution, aerial imagery over Mangrove Sanctuary, Area H on Fig. 16.

Mangrove Sanctuary (Figure 13) is located within the Cape Range National Park. The inter-tidal mangroves stabilize the shoreline and mitigate wave and tidal action. The mangrove is an area of high biological productivity and supports large flocks of waterbirds, including internationally protected migratory species. Mangrove Sanctuary contributes to the production of Ningaloo's fishery by acting as a significant medium for nutrient exchange between terrestrial and marine ecosystems (Bancroft & Sheridan, 2000). This is a highly sensitive environmental zone, which has minimal resistance to damage and is difficult to rehabilitate (WAPC, 1996).

4.1.6 Bundegi Coastal Park

Figure 14 High resolution, aerial imagery over Bundegi Coastal Park, Area K on Fig. 16.

The intertidal areas around Bundegi Coastal Park (Figure 14) contain a high conservation value due to their high biological productivity and significance as nurseries for commercial species such as prawns (Bancroft, 1999). The Bundgei Coastal Park is on Commonwealth land and requires better management of vehicle access to the beach to minimize land degradation (WAPC, 2004).

4.1.7 Exmouth

Figure 15 High resolution, aerial imagery over Exmouth, Area K on Fig. 16.

Exmouth is located on coastal plain deposits east of the Cape Range and adjoins the western shore of the Exmouth Gulf (WAPC, 1996). Exmouth is characterized by intermittent beaches separated by low and exposed limestone anchor points along the western gulf shoreline

(Bancroft, 1999). The township is built upon the fragile karst system; therefore special consideration is required to consider the impact of development on the associated subterranean stygofauna (WAPC, 1996).

Both the Exmouth townsite and the outer settlement is rapidly expanding to provide more accommodation, shopping, commercial, industrial and tourist services and facilities. Further urban growth is either planned or underway for south of the township, including the provision of 28 hectares of residential land around the new marina to accommodate a population of approximately 5200 residents (WAPC, 2004). Murat Road is a main road linking Learmonth, Exmouth and Point Murat. From this main road other minor roads diverge off towards the direction of the coast and spread out in a fan-like shape towards the beach (WAPC. 1996).

4.2 Data Collection

In 2006, the Australian Institute of Marine Science (AIMS) and BHP Billiton commissioned HyVista Corporation to capture hyperspectral imagery over Ningaloo Reef in order to map the marine and land habitats associated with the Ningaloo ecosystem. Between the 20 April and 2 May 2006, the airborne hyperspectral sensor acquired flight data over 67 HyMap image strips and 11 individual blocks with 3.5 m spatial resolution and a spectral range of 450-2500 nm in 126 channels (HyVista corporation, 2006). The HyMap survey covered a total area of 34,000 km^2 at an average altitude of 1400m - 1500m above ground with a swathe width of 1.8 km (Hyvista corporation, 2006).

The HyMap airborne hyperspectral sensor collected light from optical frequency bands to derive remote sensing data of aerial views with pixels containing detailed spectral information (Kobryn *et al.*, 2007). It is a non-invasive tool for monitoring the area and important for assisting conservation and management. HyVista Coporation corrected the data for sunglint and atmospheric effects using HyCorr software, and delivered the data in .bit format for use in ENVI. Data for the land was further corrected by Curtin University using TAFKAA software, resulting in 109 out of 125 bands available for analysis (Kobryn *et al.*, 2007). The survey covered the Muiron Islands and land past Exmouth. As the survey was principally focused on the marine habitat of Ningaloo Reef, only a 2 km band of terrestrial data was captured inland from the coast (Kobryn *et al.,* 2007). This study focused on the terrestrial dataset, using blocks A, G, H and K highlighted in (Figure 16) with a spectral range of 109 bands for surface data.

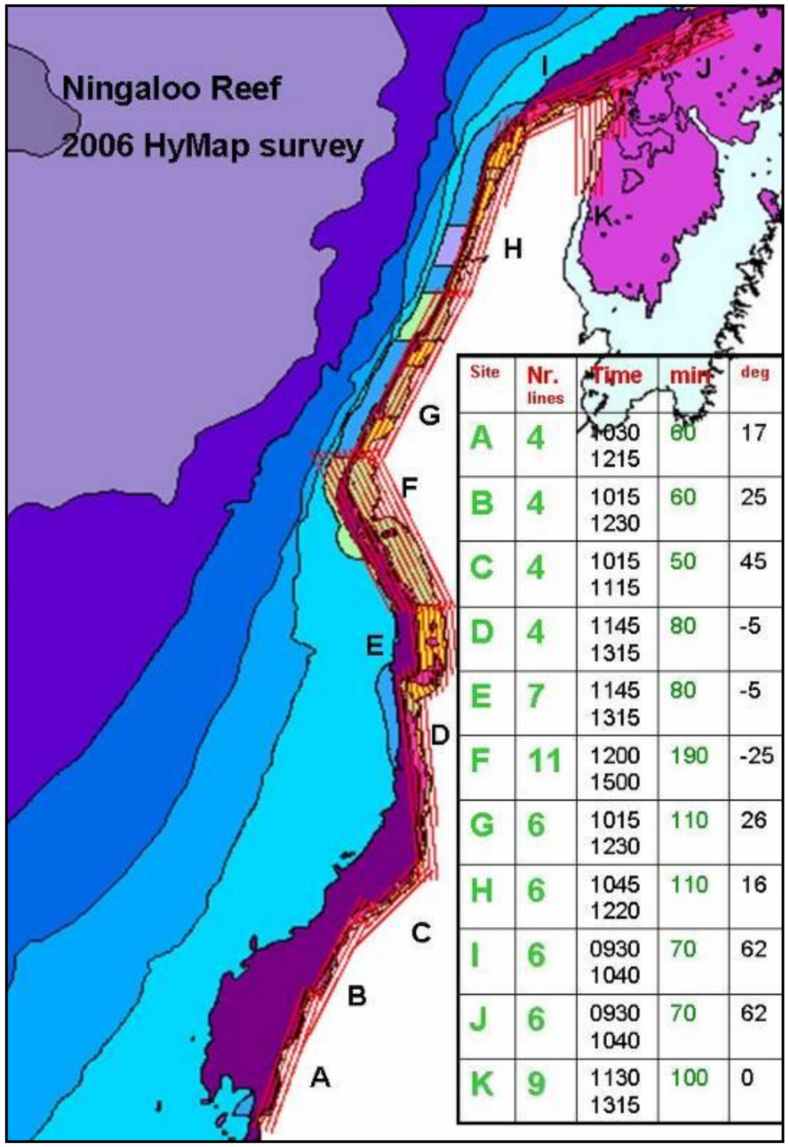


Figure 16 Ningaloo HyMap Survey Plan © Hyvista Corporation

A field trip was conducted between 21 and 27 July 2008 to ground truth the study areas. An assessment was made of the distribution and density of tracks, vegetation cover, and damage made by off-road vehicles to the vegetation and landscape. Visitor management strategies in place were also observed to assess the degree of control of the development of access tracks and traffic flow. In addition, local knowledge was acquired on the frequency of visitor use of coastal tracks and their purposefulness.

4.3 Hyperspectral Techniques

Hyperspectral sensors absorb huge amounts of information; therefore image analysis for the data requires intensive computation. In addition, spectral bands of hyperspectral data involve high interband correlations and can entail a large amount of redundancy. These disadvantages mean that efficient methods for information extraction and data compression are important in image analysis (Van der Meere & Jong, 2001).

For this study various hyperspectral approaches were used to analyse the hyperspectral terrestrial data of the Ningaloo coastline for the presence and density of tracks. These included: statistical classifiers; band ratios and vegetation indices; and spectral mixing analysis. The Minimum Noise Fraction (MNF) was also used to improve image quality. It was necessary to apply different techniques to identify tracks over different landforms, as certain methods were more appropriate for detecting the tracks on particular landscapes and vegetation than others.

4.3.1 Vegetation Indices

Vegetation Indices (VI) are a type of image transformation designed to highlight particular biophysical features/variables of vegetation. Using the reflectance properties of vegetation each of the VI highlights particular biophysical properties of vegetation, such as the presence of leaf pigment, canopy water, lignin, moisture and senescent carbon. VI are useful for displaying the condition of vegetation and for geographically mapping vegetation components to identify the status of ecosystems (ENVI, 2004).

For this study VI were applied to the analysis of the hyperspectral imagery to identify and then exclude the vegetation, so that bare areas were revealed and accentuated, including sand and limestone tracks, bitumen roads and carparks. This study mainly used Normalised Difference Vegetation Index (NDVI) for the green band in viewing the data and Plant Senescence Reflectance Index (PSRI) for the red band and Moisture Stress Index (MSI) for the blue band were also explored.

Normalised Difference Vegetation Index (NDVI)

Normalised Difference Vegetation Index (NDVI) is a broadband greenness index with high absorption and reflectance regions of chlorophyll. It is ideal for measuring the quantity and quality of photosynthetic material in vegetation and determining the vegetation condition (Van der Meere & Long, 2003). The differences between the near infrared and red ranges are nomalised through the formula:

$$NDVI = \frac{\rho\ NIR - \rho\ RED}{\rho\ NIR + \rho\ RED}$$

Plant Senescence Reflectance Index (PSRI)

Plant Senescence Reflectance Index (PSRI) is designed to provide a measure of stress-related pigments. It is sensitive to the proportion of bulk carotenoids to chlorophyll. An increase in PSRI indicates plant canopy stress, (carotenoid pigment). Where there is no vegetation, neither carotenoids nor chlorophyll are present so the plant senescence index is not detected (ENVI, 2004). The formula for calculating plant senescence reflectance index is:

$$PSRI = \frac{\rho\ 680 - \rho\ 500}{\rho\ 750}$$

Moisture Stress Index (MSI)

Moisture Stress Index (MSI) measures the water content in foliage canopy, which is related to the health of the vegetation. As the quantity of water in leaves increases so does the absorption at 1599 nm. The absorption at 819 nm is used as a reference measure as it is unaltered by changes in water content (Hill & Megier, 1994). The equation for MSI is:

$$MSI = \frac{\rho\ 1599}{\rho\ \ 819}$$

Normalised Difference Lignin Index (NDLI)

The Normalised Difference Lignin Index (NDLI) segregates the woody dead material, such as leaf litter and dry sparse vegetation from the green foliage. Lignin has a high absorption in the ultraviolet at 280nm, and in the middle infrared at 1450nm, 1680nm 1930nm and 2100nm (Hill & Megier, 1994). It was used in this study to increase the spectral contrast between vegetation conditions and bare tracks.

4.3.2 Minimum Noise Fraction (MNF)

The Minimum Noise Fraction (MNF) is derived from and similar to Principal Component Analyis (PCA). It is designed to isolate or remove noise from the data that may occur in the original bands (ENVI, 2004). It is particularly useful in hyperspectral data where the signal to noise ratio (SNR) may vary considerably in different bands due to various signal levels (ENVI, 2004). MNF maximises the SNR represented by each component to create improvements in image enhancement and information extraction. This study employed 20 transformed bands with various combinations of channels to display the imagery.

4.3.3 Spectral Angle Mapper (SAM)

The Spectral Angle Mapper (SAM) is an automated method for comparing image spectra to known spectra. This method treats both (the questioned and known) spectra as vectors and calculates the spectral angle in between (ENVI, 2004). The result of the SAM classification is an image showing the best match at each pixel.

The spectral unmixing technique interprets one pixel as representative of a class of signatures in that given pixel. Therefore, if three different classes are apparent in one pixel, such as 25% was represented as bare sand, 25% green vegetation and 50% dry vegetation, from these values the mean pixel coverage was determined by Envi software. The signatures of tracks were collected and their particular mineralogy to estimate the type of track surface. The mineralogy included parameters such as quartz, limestone and clay components as well as iron oxides which drive the colour of soils in the area.

4.4 Aerial Photography

Standard aerial photography has only 3 visible bands and 2m pixel resolution. The aerial imagery cannot be used for automatic extraction of tracks. This needs to be achieved manually by digitizing the minor roads. Tracks over certain areas of Ningaloo's coastline were digitised by students of Curtin University, which provided an indication of the distribution of tracks. Further tracks were digitised in this study from the mosaiced images in ArcView GIS. Access points related to a clear track or path leading to a beach were also digitised to show which sections of the coast were clearly used.

5.0 Results

5.1 Pastoral Lease

From the interpretation of hyperspectral imagery and ground-truthing observations at study areas south of Yardie Creek, it was observed that there was little control over the development and spread of tracks along the coastline. The analysis showed tracks diverging off in a fan shape towards the foredunes and beaches, creating various access routes for visitors.

5.1.1 Gnaraloo Bay

Certain major tracks were visible crossing through the landscape with NDVI (Figure 17a), providing a contrast between sparsely, green vegetated areas and soil. However, bare areas, such as rocky headlands and foreshores were reflected in similar hues as the tracks, making it difficult to identify the minor tracks along the foredunes. The application of MNF improved the detection of these tracks (Figure 17b), showing them running parallel to the shoreline and spreading out chaotically through Acacia and Spinifex vegetation. The red rectangle in the top image contains the output in the lower image.

a b

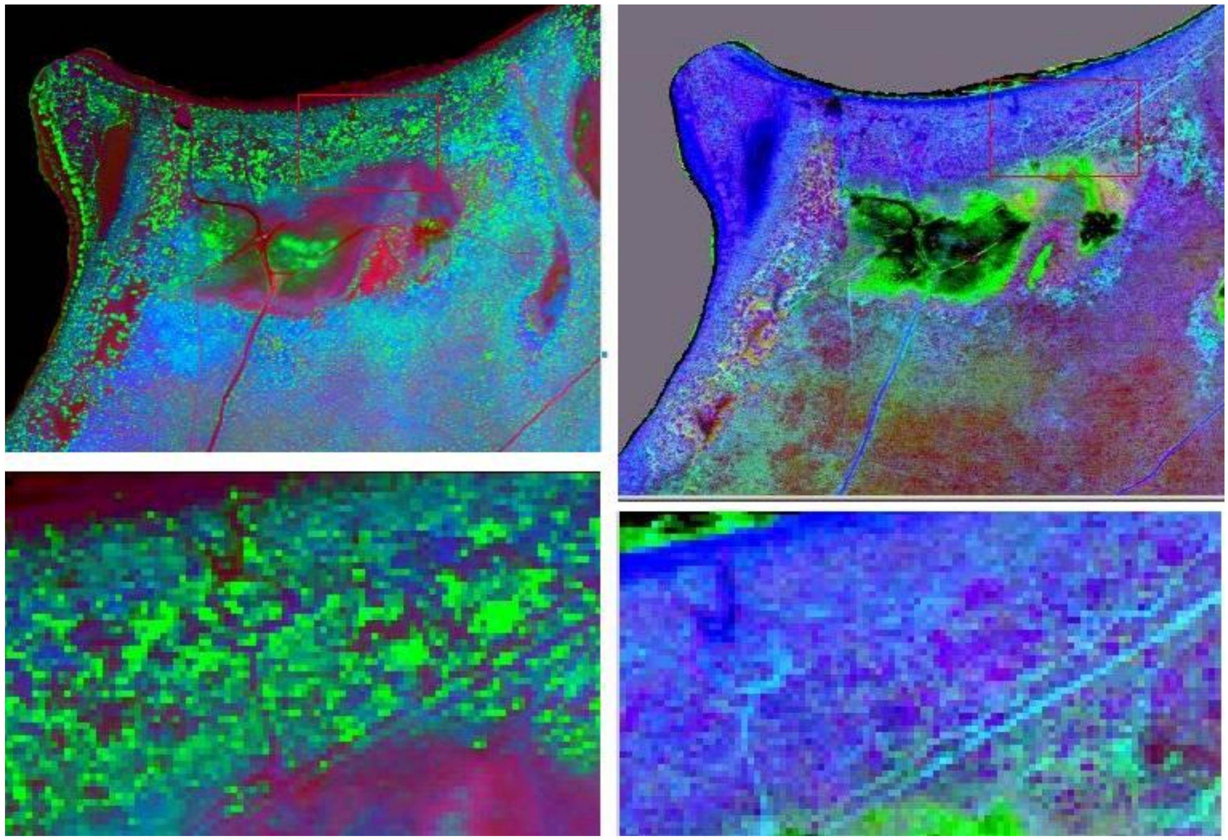


Figure 17 a) NDVI displays vegetation along the foredunes of Gnaraloo Bay and the headland as bright green, beaches and bare sandy tracks in purple and red hues and drier vegetation in blue. b) MNF (bands 6, 7, 8) shows 3 sand tracks spreading towards the foredunes in aqua.

Various colour palettes of SAM provided different spectral contrasts. Narrow tracks running parallel and perpendicular to the coast were detected along the western shoreline (Figure 19a) and south of the headland, developing in a fork and triangular shape (Figure 19b). Tracks were mapped criss-crossing through dunes and dry grass (Figure 19c), as well as heading east along the shoreline (Figure 19d). The reflectance spectral plot (Figure 18) provided an indication of the type of surfaces of the tracks, such as sandy or limestone by showing the reflectance of ground cover materials.

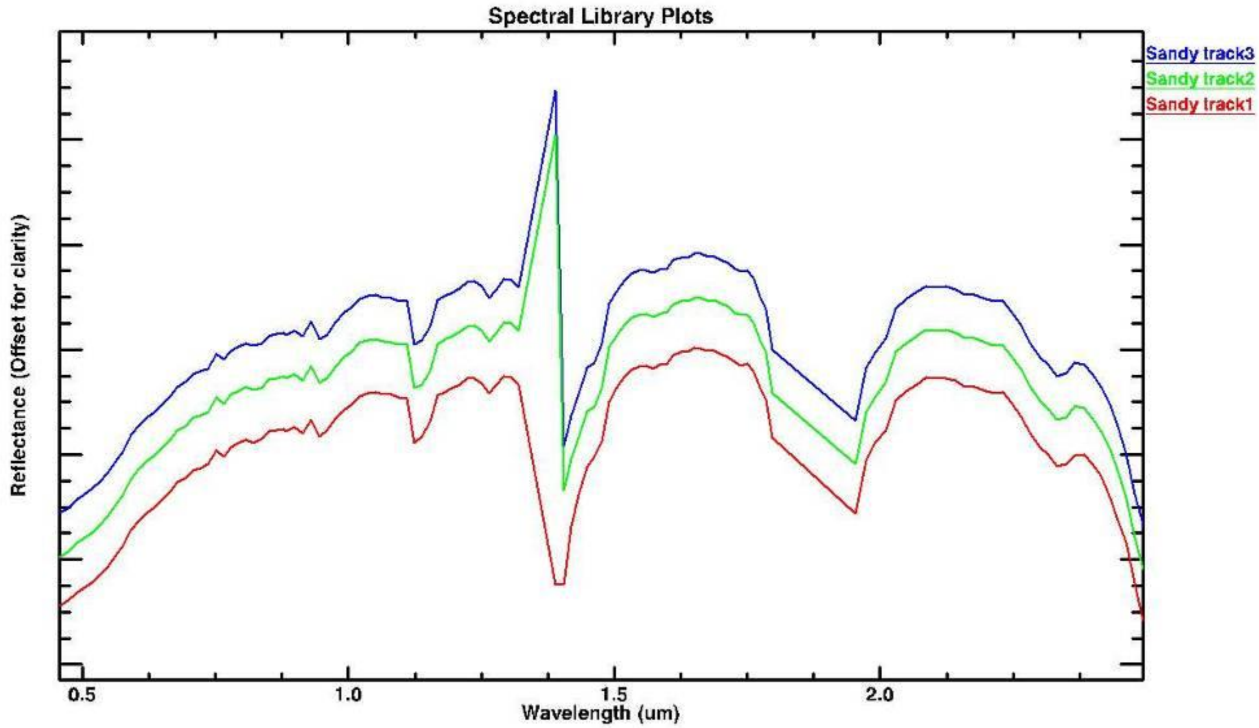


Figure 18 A reflectance spectral plot of sandy tracks from the subset of data of Gnaraloo Bay, that offsets spectra. It displays the absorption features due to water content: 1.4µm and 1.9µm. and due to calcite: 2.38µm.

a

b

c

d

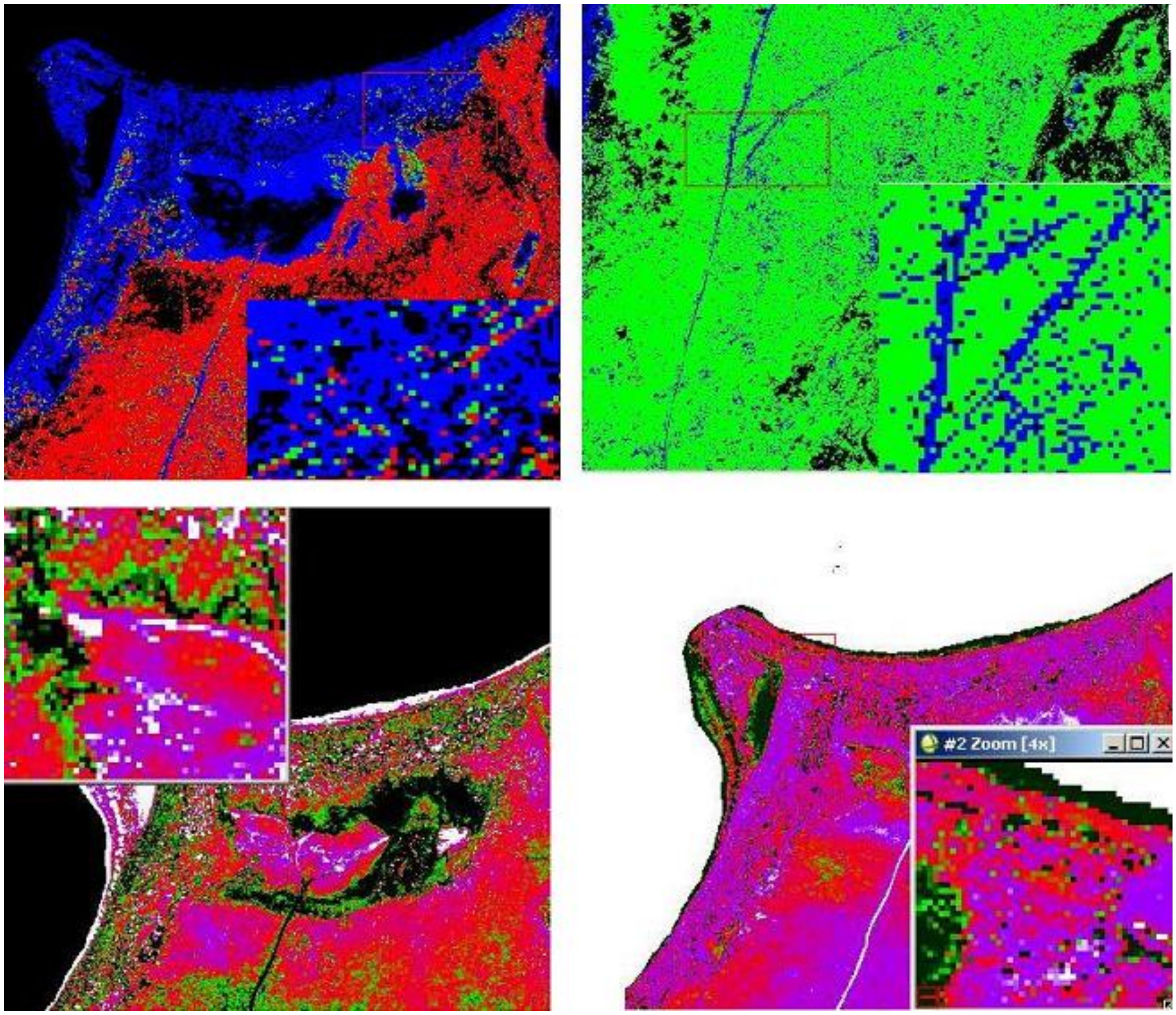


Figure 19 Hyperspectral signatures showing a) one long track heading west behind the foredunes is displayed in red, using RGB, b) a triangular development of tracks south of the headland is shown in blue with green and blue hues, c) several criss-crossing sand dune tracks are observed in black in a green-red-blue and white pallette and d) adjusting the minimum/maximum of the same pallette as c) reveals two tracks developing west along the shoreline in black.

5.1.2 Winderabandi Point

Individual plants, such as Spinifex and Acacia were detected at Winderabandi Point with NDVI (Figure 20a), as well as fine, faint, lines along the shoreline, which indicate several tracks. However, it is difficult to discriminate the fine sand tracks from the bare or sparsely vegetated areas, even with the NDLI (Figure 20b). The bare patch at the point could be interpreted as an unsupervised camping area, or the result of wind blow outs and natural erosion. To gain an improved understanding of the area some ground-truthing would be required. Given the challenge of identifying the tracks for this particular node, it could be a good candidate for hand digitizing with high-resolution aerial photography.

a b

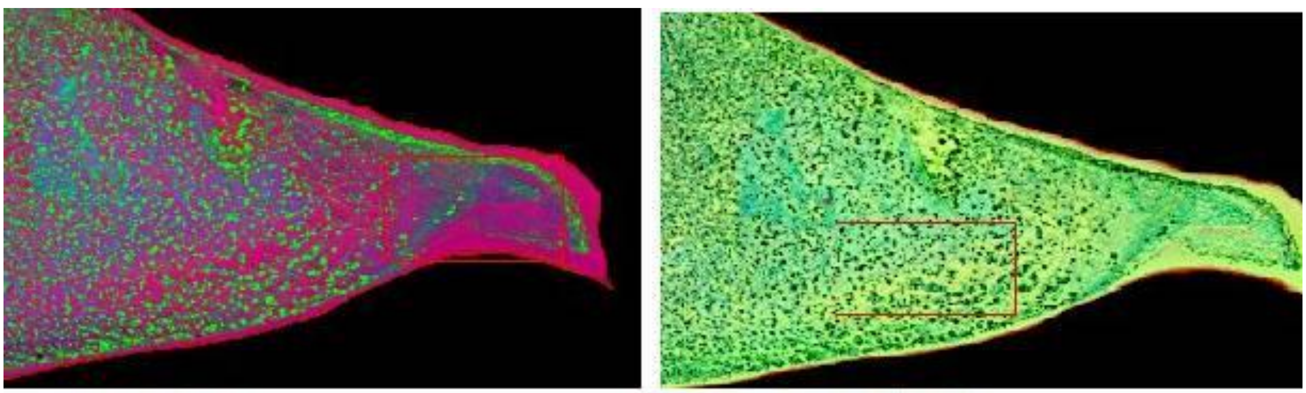


Figure 20 a) NDVI struggles to detect the fine tracks along the shoreline as both dry vegetation, bare areas and tracks are displayed in similar pink, purple hues. b) NDLI improves the display of shoreline tracks in yellow against woody material, which is classified in green hues.

North of Winderabandi Point, spectral unmixing analysis detected the mineralogy of material, such as the pink mineral component of iron in relic dunes and the quartz and limestone in foredunes. This classification helped to map the surface of tracks, such as coastal limestone tracks (Figure 22b), and sandy tracks dispersing out towards the secondary dunes (Figure 22a). The grey scale of a RGB composite image (Figure 22c) reveals a finer network of minor tracks crossing over the primary foredunes better than the true colour composite (Figure 22d).

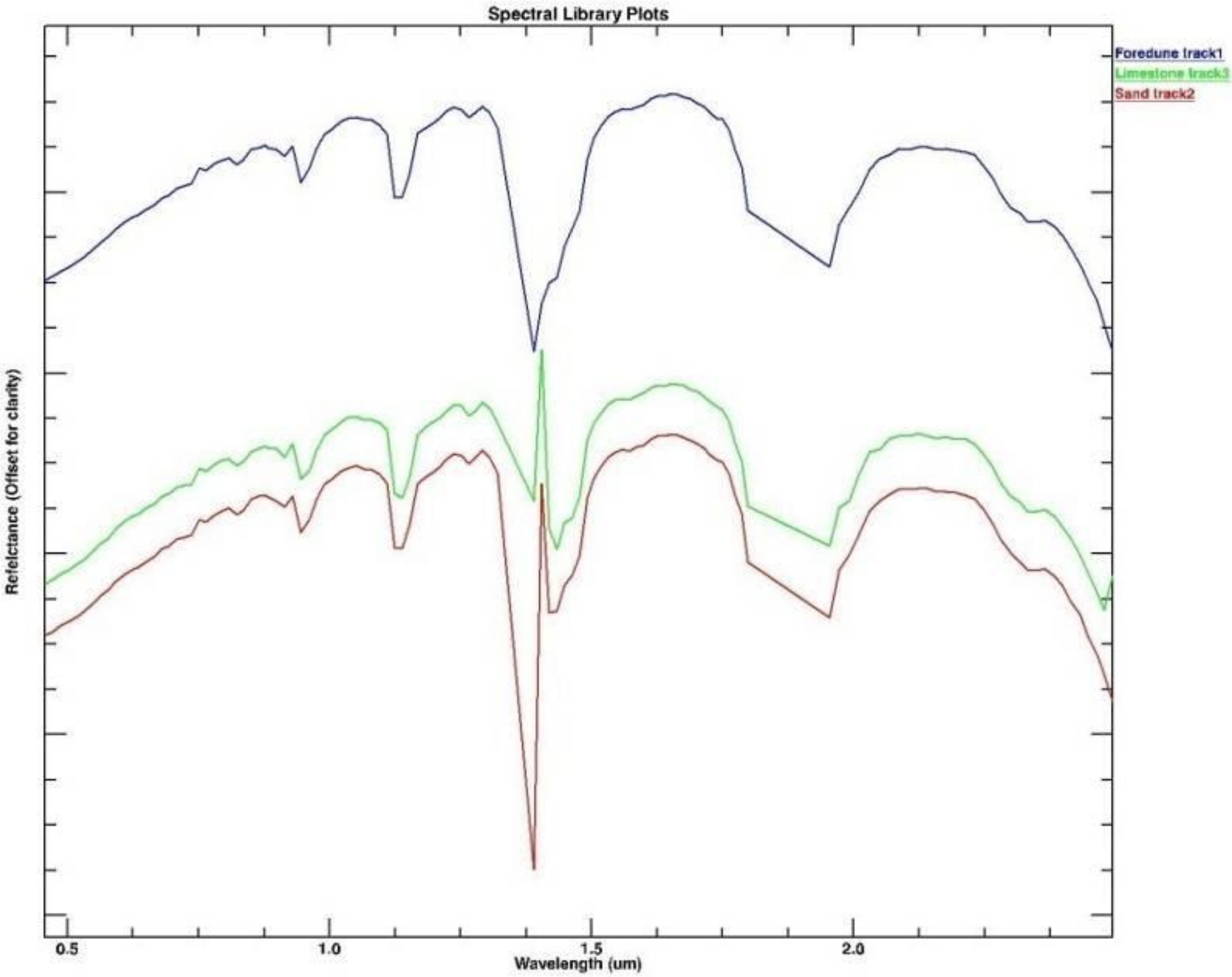


Figure 21 The graph shows the spectral profile for north of Winderabandi Point. Signatures were extracted to display reflectance for sandy, limestone and foredune tracks.

a b

c d

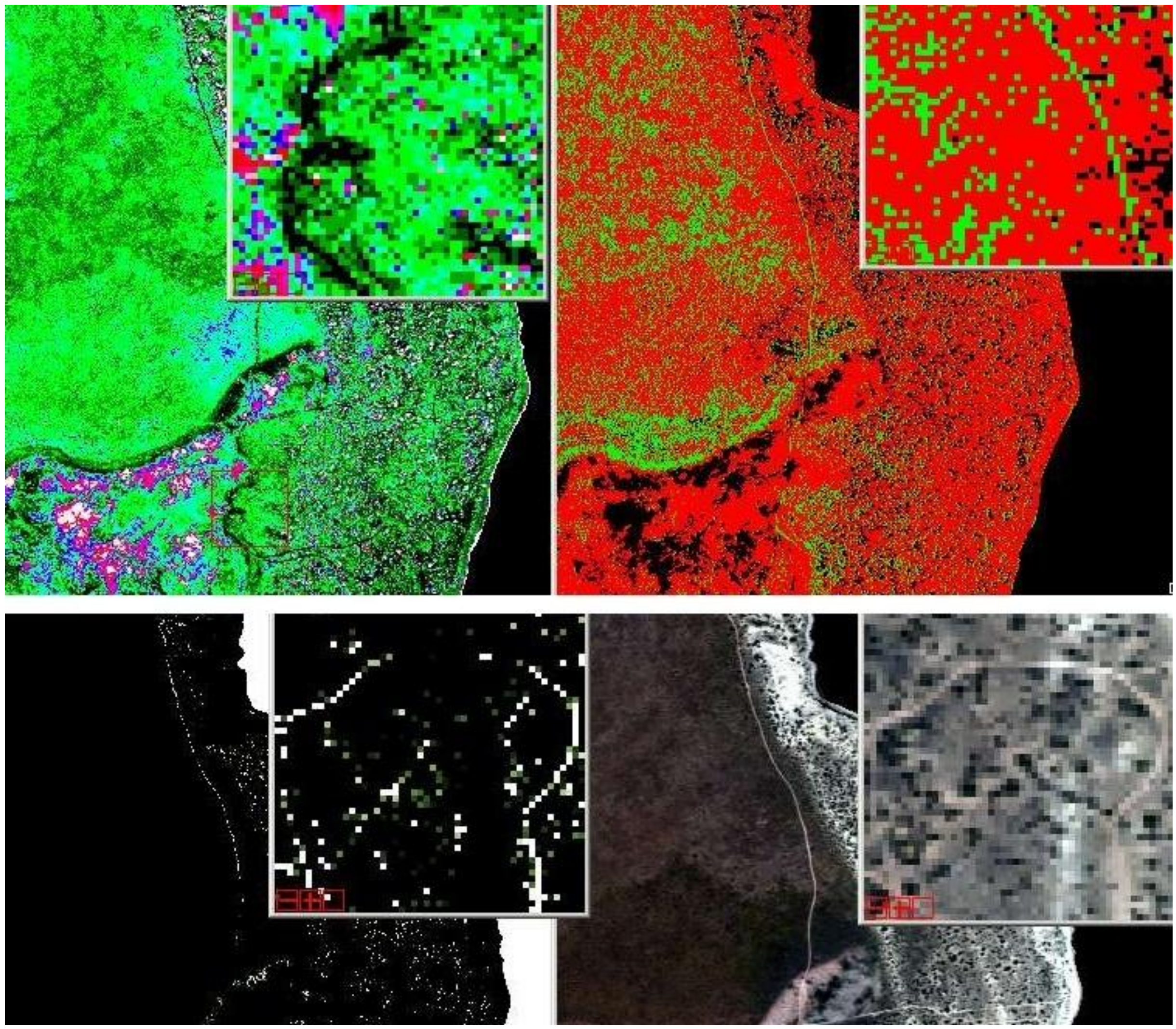


Figure 22 Hyperspectral signatures detect a) sandy dune tracks displayed in '16 level' palette and b) a major limestone coastal track is identified in green. c) Shoreline tracks are detected in white in grey scale, RGB composite image, better than in true colour RGB image d) by creating more contrast, however they are less continuous.

5.2 Cape Range National Park

Within Cape Range National Park effective management was observed of roads, tracks and paths that had been aligned and constructed to minimise habitat degradation and disruption of native fauna movement patterns. Track closures, fences, carparks, signage, spur roads and rubbish collection have been erected to appropriately direct visitors to the coastal access points and discourage vehicles from driving over vegetation and throughout sand dunes. In fragile environments, boardwalks and fenced walkways have also been constructed to prevent trampling, such as at Mandu Mandu. In addition, the Department of Environment and Conservation has moved the original coastal road back from the coastline and provided numerous access roads to popular camping and picnic areas along the beach (WAPC, 1996). To encourage rehabilitation of the old road, measures have been taken to block vehicle traffic accessing the area.

a b

c d

Figure 23 a) Access road closed to vehicles near mangroves at Yardie Creek. b) Fences erected at Tulki beach to prevent vehicles travelling over dunes. c) Original coastal road closed for rehabilitation. d) Signs around carparks for directing visitors to the beach.

5.2.1 Yardie Creek

The Moisture Stress Index of the NDVI (Figure 25a) identified the presence of the original coastal road that is becoming vegetated, as this index displayed low moisture content in comparison with the nearby vegetation. Ground truthing along certain segments of the original coastal road determined that the track is 3 metres wide and relatively undisturbed by vehicle traffic and native plants were colonizing the track (Figure 24).

Figure 24 Ground truthing around Yardie Creek, observed that the old coastal track has new native vegetation.

The NDLI (Figure 25b) complimented the NDVI image by distinguishing between the green mangroves and the dry, dead plant material, in order to accentuate the minor tracks. The track heading south of Yardie Creek and four tracks diverging off from the north towards the beach were clearly highlighted with the NDLI. The old coastal road was detected better with MNF by showing different spectral components of the landscape (Figure 25c).

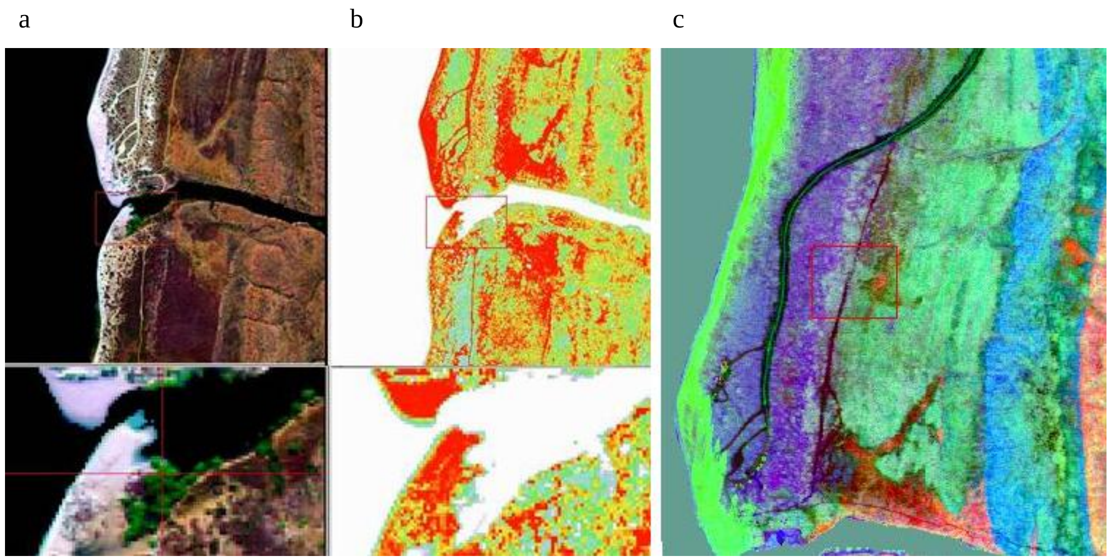


Figure 25 a) NDVI displays mangrove vegetation as bright green and tracks as white heading down to the shoreline of Yardie Creek. b) NDLI shows woody plant material as light green and tracks heading south and north as red. c) MNF (3,4,5) detects the old coastal road in brown.

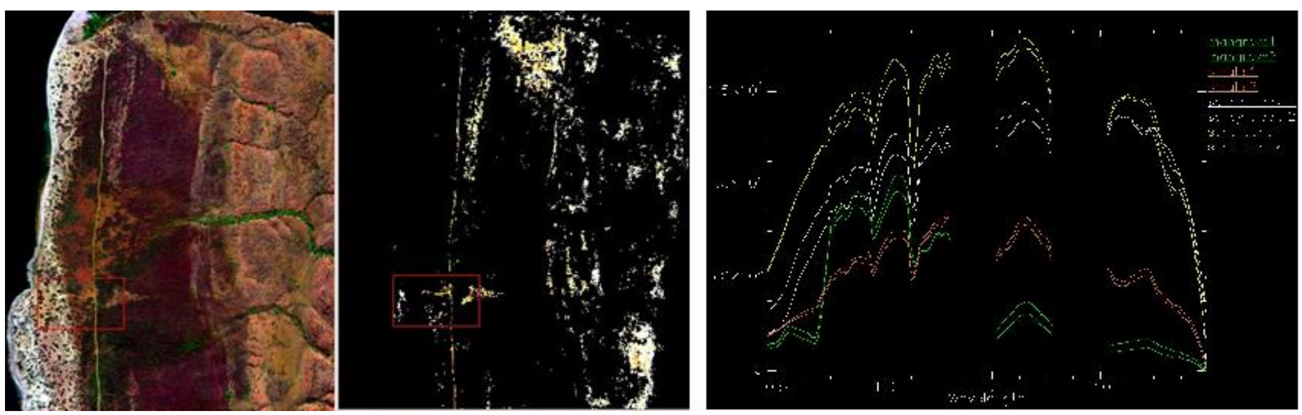
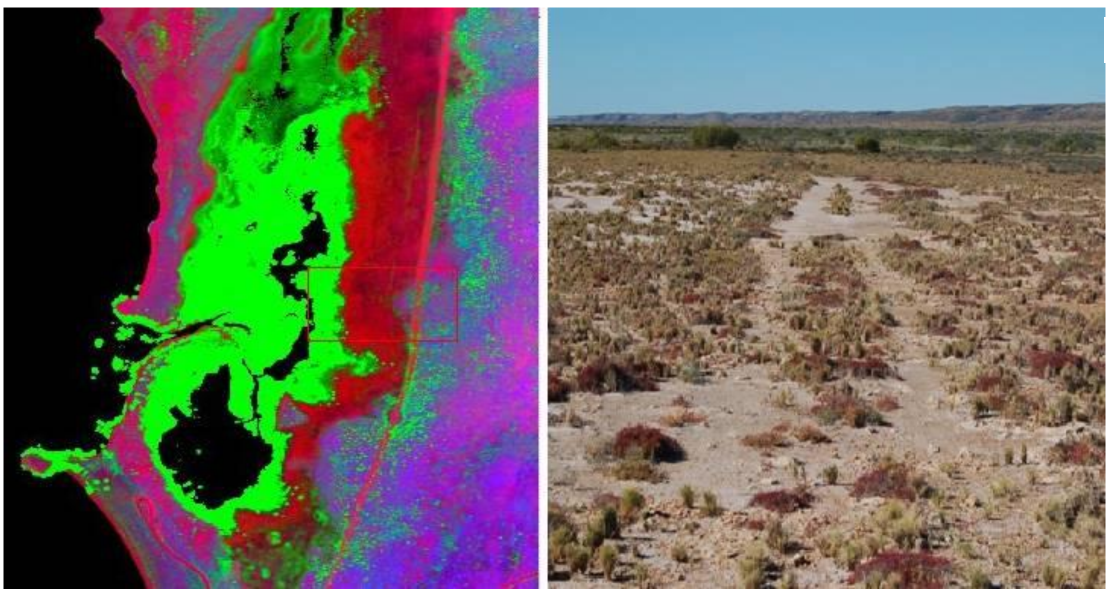


Figure 26 Separate components of the landscape around Yardie Creek are mapped with different spectral signatures for mangrove, sand, dry grass substrate from the spectral profile.

5.2.2 Mangrove Sanctuary

From ground truthing areas around Mangrove Sanctuary it was observed that there were few tracks diverging off from the carpark near the beach and in general it was well maintained, showing little disturbance to the vegetation cover. The MNF image (Figure 27) highlighted the original coastal road passing behind the mangroves over the saltpan. The track did not appear to be frequently used, however it was not closed and although some plant colonization was occurring, the track was still clearly visible.

a

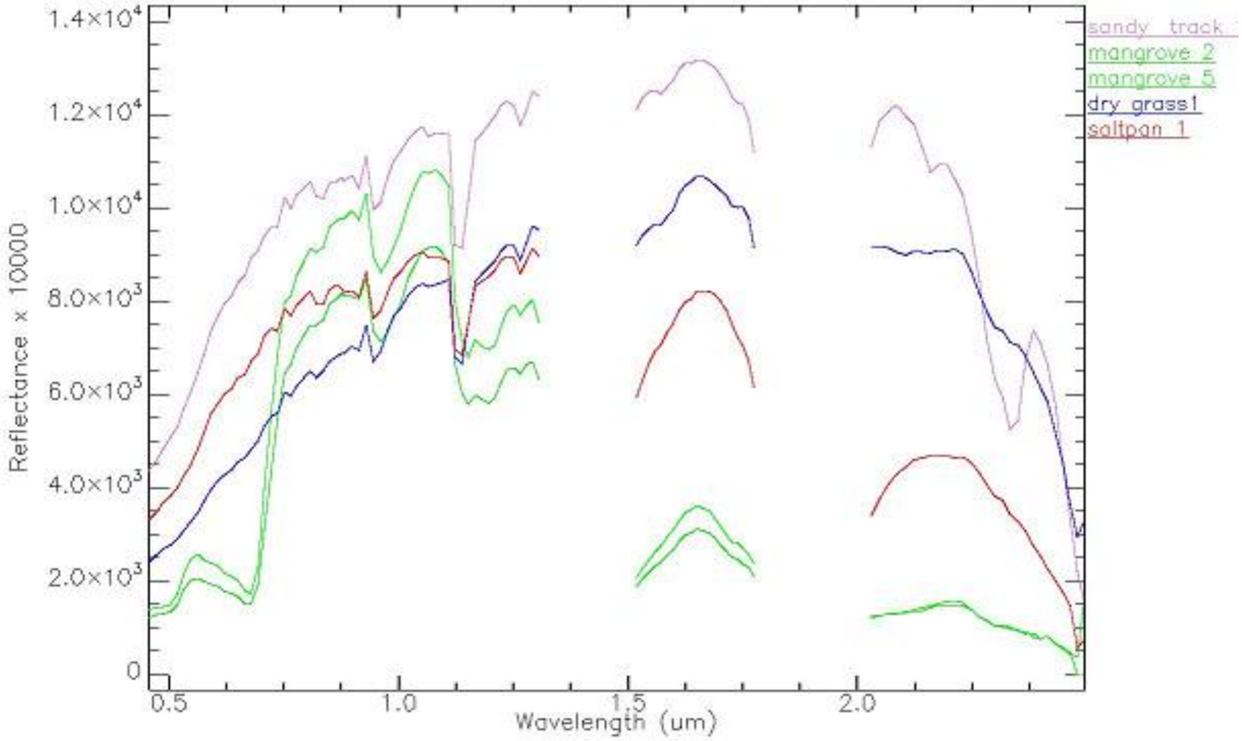


b

Figure 27 a) MNF image highlights the old coastal road passing behind the mangroves in red. b) Ground truthing showed that the old road was used infrequently.

Using spectral unmixing techniques, signatures were extracted over certain areas to classify mangrove, sand, drygrass and saltpan components (Figure 28). The data was verified with information that had been acquired from field observations near the mangroves, in order to interpret the imagery more accurately (Figure 28).

a



b

Figure 28 a) Spectral signatures were obtained to reflect the various types of substrate, such as sand, mangrove, and dry grass. b) Ground truthing areas to determine surface cover and track distribution.

The tracks near the shoreline of the mangroves were detected in the hyperspectral signature image (Figure 29b). The hyperspectral probability signature (Figure 29d) best detected tracks splitting off from the old coastal road behind the mangroves over the saltpan in yellow hues.

a b c d

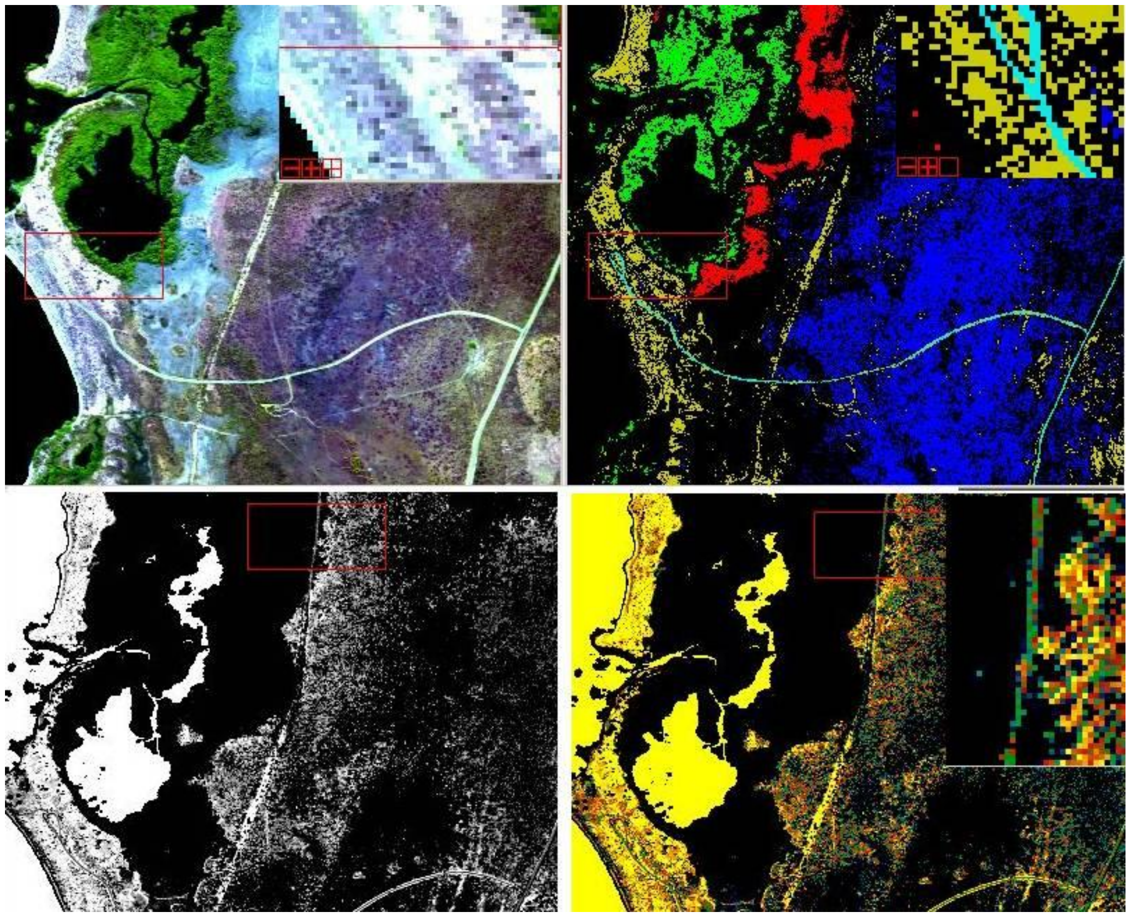


Figure 29 a) True colour RGB composite image (channel 56 for red, 21 for green and 8 for blue) detects mangrove vegetation in green, saltpan substrate in light blue and the main track in white. b) Hyperspectral signature displays minor tracks near the shoreline of mangroves in light blue. c) Probability signature detects the track splitting off from old road in white. d) The track splitting from the old road is enhanced with blue, green and yellow hues. The black areas has not been classified as there was no spectra match to the spectral library, which in this case was pixel with a match between 0 and 0.04 radians.

5.3 Commonwealth Land

In contrast to the Cape Range National Park, where the flow of traffic appeared fairly well contained, around the north of Exmouth, there was much less management of vehicle traffic observed. This has resulted in a network of indiscriminate tracks and uncontrolled access routes to the beach, carved out across the mudflats and tidal plain.

5.3.1 Bundegi Coastal Park

Around Bundegi Coastal Park there were extensive tracks through the mudflats and tidal plains, with new tracks made in the substrate to access the beach. As there is low vegetation cover, vehicles can easily create new tracks across the terrain. Consequently, the surface of the tracks over the mudflats appeared compacted and rutted (Figure 30).

Figure 30 Ground truthing Bundegi Coastal Park, showed many tracks spreading across mudflats.

The NDVI (Figure 31a) displayed the major tracks traversing over the dry Samphire vegetation. The NDLI (Figure 31b) highlighted some of the minor tracks developing over the mudflats near the shoreline; however this network of narrow tracks was the most visible with the application of MNF (Figure 31c). The use of SAM provided an indication of the distribution of tracks winding further south east towards the beach (Figure 32).

a b c

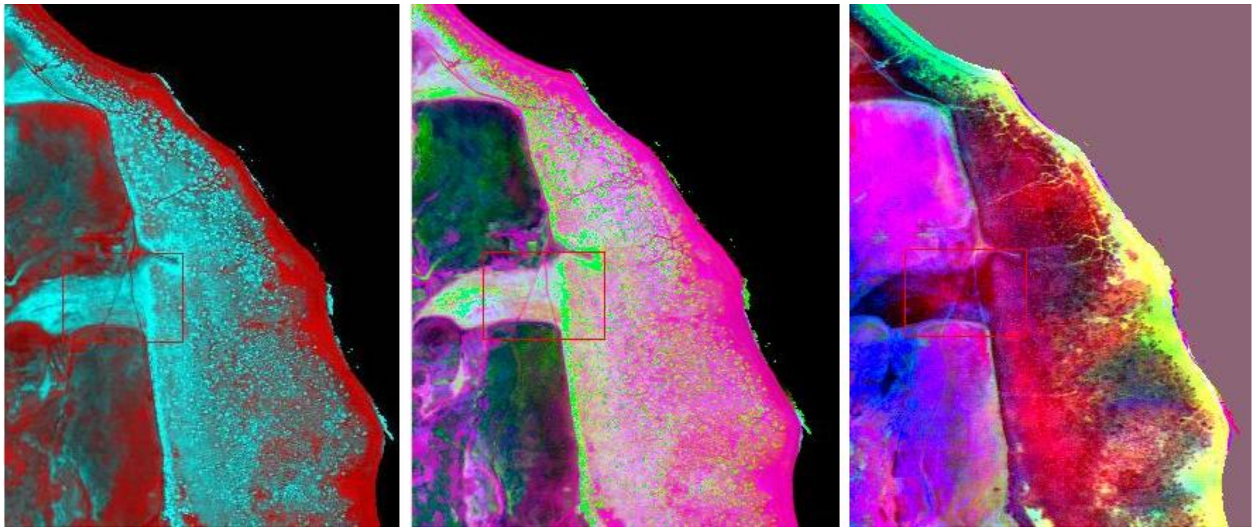


Figure 31 a) NDVI over Bundegi Coastal Park detects moisture stress in blue over the mudflats and bare tracks, beach and dry vegetation in red. b) NDLI shows faintly a spread of minor tracks over mudflats in pink. c) MNF 20 displays best a network of shoreline tracks in yellow.

a b

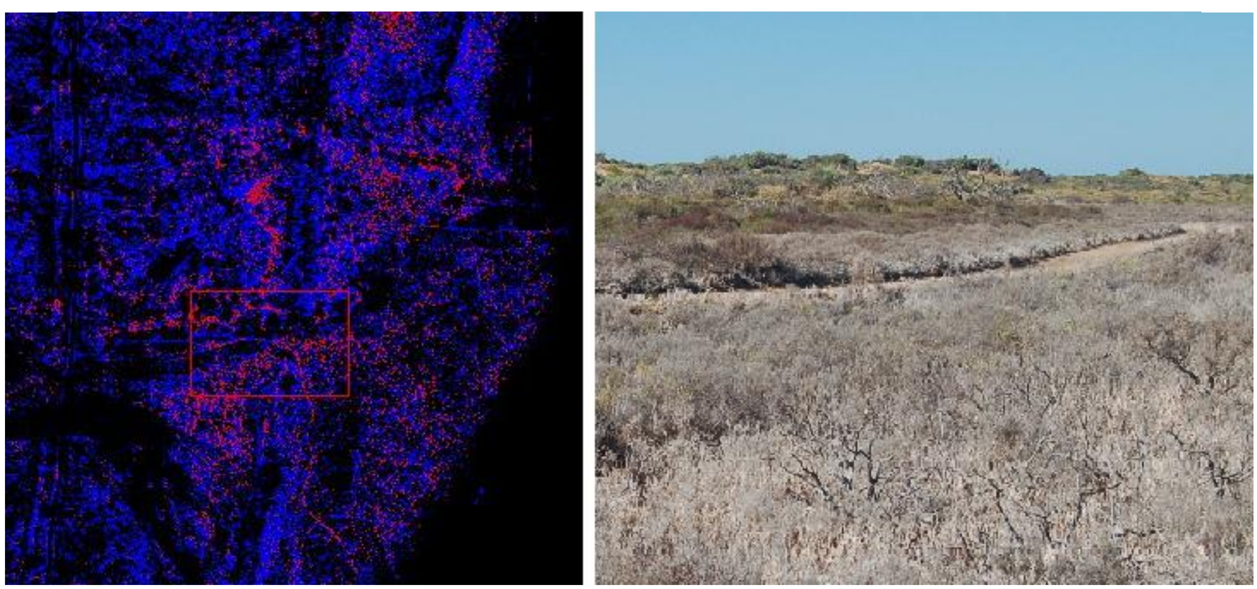


Figure 32a) Hyperspectral signature over Bundegi Coastal Park detects tracks over mudflat substrate in red. b) Example of type of tracks in the area.

The high resolution aerial imagery (Figure 33) displayed some of the major roads distributed around Bundegi Coastal Park that had been hand digitized and some of the minor tracks that had been both digitized and ground truthed.

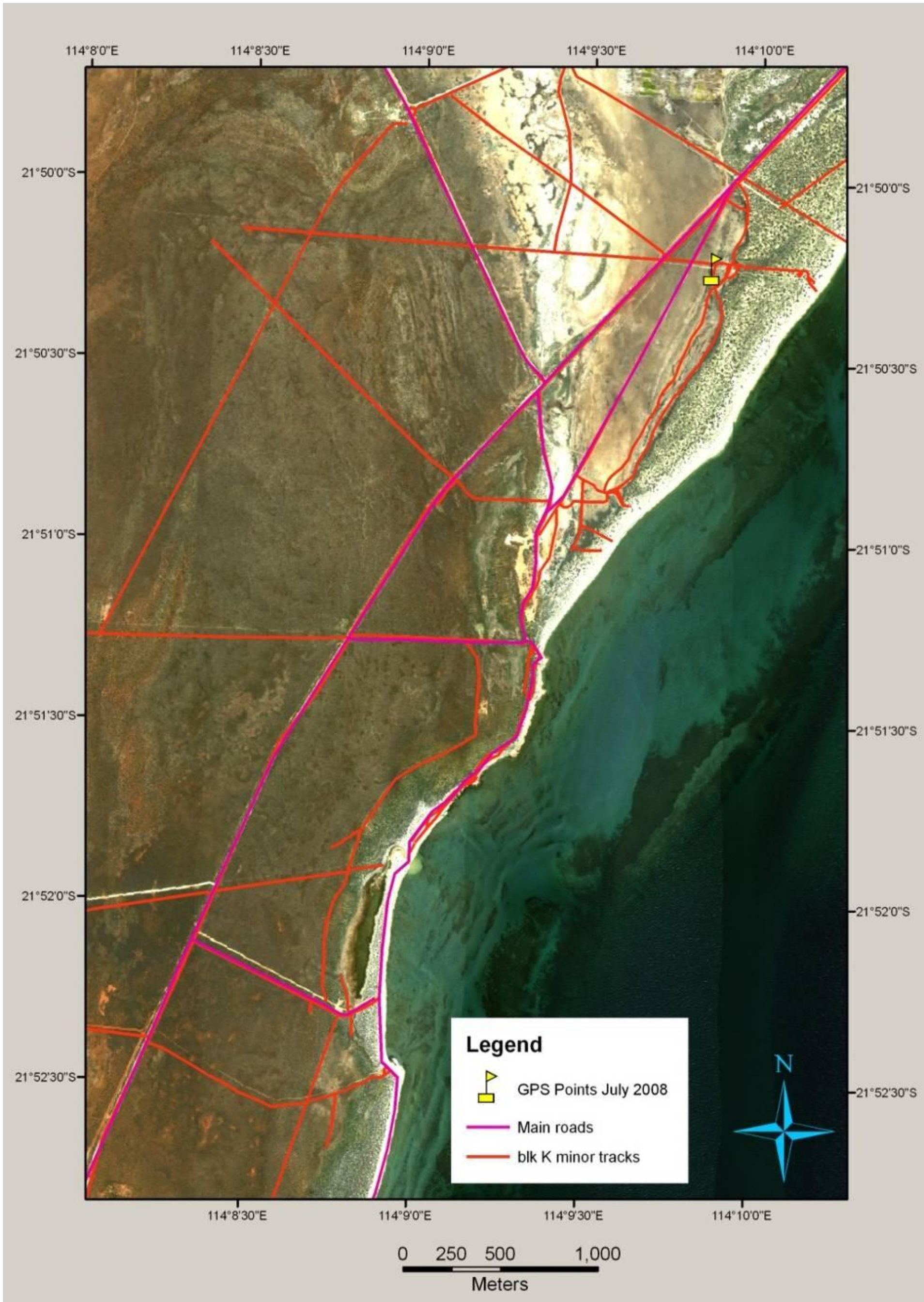


Figure 33 High resolution aerial image displays digitized main roads in pink and the spread of minor tracks in red around Bundegi Coastal Park. Ground truthed locations are represented with yellow flags.

5.3.2 Exmouth

Whilst, ground truthing areas south of Exmouth, many 4WD vehicles crossed over the coastal vegetation and along the beach. A motorcyclist even became bogged in the sand and needed assistance removing the vehicle (Figure 34). There appears to be much less management of vehicle access to the beach than in Cape Range National Park. Vehicle operators appeared to be creating new tracks across beaches when existing ones had become boggy, rough or impassable, causing the disturbance to shoreline vegetation (Figure 35).

Figure 34 Whilst ground truthing an area south of Exmouth, a motorcyclist got bogged in the beach sand.

Figure 35 Vehicles pass frequently over the beach and damage shoreline vegetation.

The NDVI (Figure 36a) struggles to detect tracks over the dry shrubland, however, the NDLI (Figure 36b), creates a better contrast between the vegetation types and thus reveals tracks running parallel and perpendicular to the beach south of the newly built marina at Exmouth.

a b c

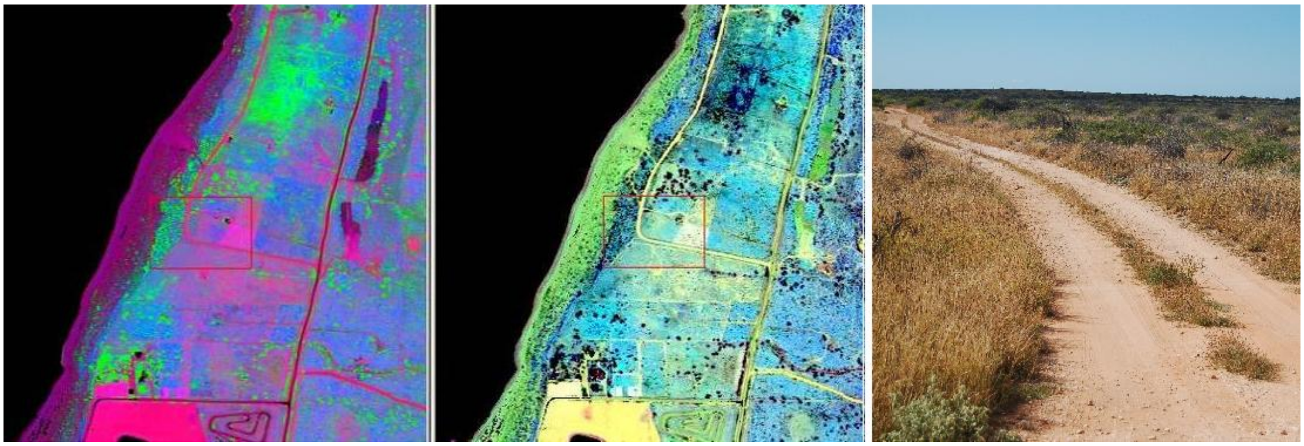


Figure 36 a) NDVI shows faintly tracks in pink heading towards the beach. b) NDLI detects more minor tracks along the shoreline in yellow. c) The type of tracks observed diverging off from main Milnya road and the type of dry vegetation.

a b c

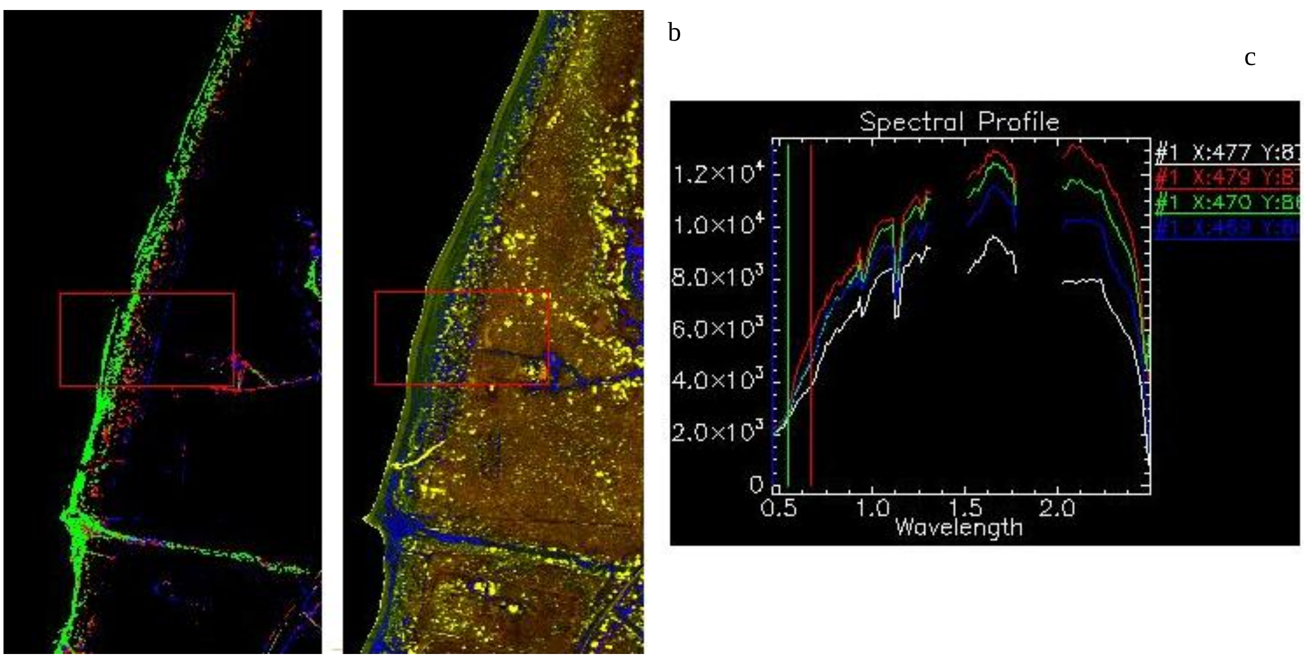


Figure 37 a) Hyperspectral signatures detect tracks running along the shoreline in blue, b) the probability signature identifies finer tracks on the foredunes in yellow. c) Spectral profile of signature of tracks South of Exmouth.

6 Discussions

6.1 Using hyperspectral imagery for mapping tracks

The results have shown several hyperspectral mapping techniques for analyzing the presence and distribution of tracks, as well as access nodes to certain sections of Ningaloo's coastline. The various techniques applied have had different results for identifying tracks along different landforms and habitats, including a range of vegetation conditions and soil types.

The detection of the tracks was achieved partly by mapping the vegetation with Vegetation Indices to enhance the spectral contrast of vegetation in the landscape, while minimizing the influence of other processes (Hill and Mégier, 1994). The VI offers a fast qualitative assessment of the presence of vegetation over large areas however, they have their limitations due to the similar character of vegetation spectra and absorption features (Schmidt & Skidmore, 2003). In a semi-arid environment these drawbacks make it particularly difficult to use NDVI to classify the photosyntheically active vegetation, as much of the environment consists of either dry, woody plant material or bare soil (Asner *et al.,* 2000). The application of other vegetation indices, such as lignin, plant senescence and moisture stress indexes served to improve the spectral contrast between the dry or sparse plant material and greener foliage and thereby, highlight the tracks. Further exploration of Vegetation Indices could be carried out using the Moisture Stress Index to detect the rate of recolonisation of closed access routes, such as the old coastal track by observing the increase in the moisture index over time. Since changes in vegetation and soil conditions can offer significant clues for degradation of habitat, such as erosion (Hill *et al.*, 1994) further analysis of the Ninglaoo dataset could provide an indication of the impact of excessive vehicle traffic on vegetation.

The use of MNF displayed spectrally different coloured components of the material in the landscape, such as rocky shorelines, which helped to distinguish the minor tracks against these features. Different spectral channels were more appropriate over particular surfaces, for example bands 5, 6 and 7 worked well over mudflats near Bundegi, while 1, 2 and 3 had clearer results over the saltpans at Mangrove Sanctuary.

In areas of sparse vegetation cover, bare or sandy areas, where it was difficult to detect tracks with indices, the spectral unmixing approach was applied. The application was linked to the principle that the ratio of material in the signal that is detected by the pixel resembles a proportion of the ground cover of this material. This allows the ratio of material within the pixel to be quantified (Muller *et al*., 2004). The automated signature approach applied in this study was able to extract the spectral signature of tracks to determine their surface or mineralogy (e.g. sand, limestone and saltpan). This technique was the most appropriate for areas where there was little vegetation and thus a minimal amount of spectral contrast to detect the tracks.

The high-resolution aerial photography with digitized roads provided an indication of the spread of tracks over the landscape. Within 1m pixel resolution, tracks stood out more clearly than the hyperspectral imagery (3.5m spatial resolution) however, it lacked information on whether minor tracks were present and it was unable to provide information on the type of vegetation, condition or soil, including the surface of the tracks. In contrast the hyperspectral techniques allowed for quick and relatively easy detection of tracks over large areas, providing data on the range of landforms.

6.2 Limitations of study

If more time was available for the study, further ground truthing of areas and field observations could have been carried out south of Yardie Creek to gain a more comprehensive understanding of the distribution of tracks and their impact on the coastline. This could have assisted with interpreting the hyperspectral imagery for tracks at high intensity nodes, for example near Winderabandi Point. Additional research could monitor the changes in track making and vegetation over time and use this dataset as a baseline for information for particular nodes. Further analysis of the tracks could also obtain more accurate and detailed results, by refining the data and creating mask. A quantitative assessment could also be carried out to evaluate the density of tracks. In addition, there is an opportunity to digitize more tracks shown in the aerial photography to compare with future datasets.

As the original research was principally concerned with the marine habitat, the HyMap survey was flown over April after the Summer months to accommodate favourable wind and wave conditions for the acquisition of data. Therefore, vegetation was generally in a dry condition, which caused some difficulty in using the vegetation indices for analyzing the imagery, as there was less contrast between the vegetation and bare tracks. To improve the research another HyMap survey could be flown over more of the terrestrial landscape, after cyclonic rains when the vegetation has a higher chlorophyll content to detect photosynthetic active plant material.

6.3 Significance of dataset for management

This study has evaluated selected areas to observe the presence of certain tracks, in terms of providing vehicular access to coastal area for visitors and residents. Overall, from the combination of analysis of hyperspectral imagery and field observations it appears that there is less management of off-road vehicle traffic for areas outside Cape Range National Park. The results from this hyperspectral dataset can provide an indication of the type of hyperspectral techniques that can be applied for assisting with the monitoring and management of vehicle traffic along the Ningaloo coastline.

The long-term environmental impacts to coastal communities, associated with the opening up of coastal areas through the provision of new roads are an important consideration for conservation of the Ningaloo region (WAPC, 2003). The degree of existing and future management strategies for certain areas has been discussed, along with the prevailing road network. With future tourism growing and spurring tourism development for south of Yardie Creek, as well as construction of new housing at Exmouth, it is vital that a road network is planned that places minimum impact on the coastal communities. In addition, the expiration of the pastoral leases will require that the Department of Environment and Conservation develop new tools and strategies for monitoring this large, remote area.

The roads provide a significant management tool for directing visitors to access points and portions of the coastline for sustainable use (DEC, 2002). This study has discussed how in certain parts within the Cape Range National Park, the Department of Environment and Conservation is closing old tracks and constructing more suitable ones. Any building of new or upgrading of existing roads should take into account the exposure this will lead to of vulnerable coastal communities by the increase of visitation and potential degradation

(WAPC, 2004). The effective structuring of roads can actually assist with conserving areas that lack sufficient management (WAPC, 2003).

This study has discussed how a balance is required between the rising demands for access and tourism experiences and those of environmental protection in Australia. The Ningaloo coastline is a remote and pristine environment; it is these unique attributes that are responsible for attracting so many tourists (WAPC, 2003). Unplanned access causing degradation of the natural resource places in jeopardy the environmental values and may erode future tourism potential (WAPC, 2004). Well planned and designed coastal link roads, with planned beach (nodal) access points will allow access by tourists without encouraging unacceptable use (WAPC, 2004).

7 Conclusions

Hyperspectral Imagery is a non-invasive monitoring tool, which is useful for monitoring large areas that are difficult to access on the ground. It has over two hundred channels, which provides better detection and identification than broadband imagery; and allows the flexibility of choosing several narrow bands for specific targets.

For the purposes of mapping the density of tracks, hyperspectral imagery can offer more information to help assess the impact of the tracks on the environment. The range of spectral bands allows for the detection of soil type and surfaces of tracks, including the mineralogy of material, as well as the analysis of whether a vegetation community is easily eroded. This information is not provided for in aerial photography.

The study can assist management by providing an indication of the type of results that are to be expected with the application of certain hyperspectral techniques for monitoring roads and improving road strategy and traffic movements.

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