THE SUITABILITY OF REMOTE SENSING FOR PRIORITISING MANAGEMENT OF INVASIVE PLANTS IN THE GARDEN ROUTE SOUTH AFRICA

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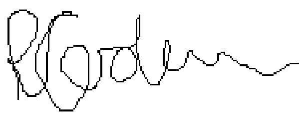
Declaration

I, Rosie Victoria Gerolemou (215384172), hereby declare that the dissertation for Masters of Science in Geography to be awarded is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.



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Contents

Abstract

Invasive tree species pose a huge problem in the Garden Route and are particularly damaging to aquatic ecosystems, including wetlands, riparian zones, lakes and estuaries. Therefore, this study aimed to determine priority areas for invasive tree species management, with a focus on aquatic ecosystems. This was achieved by using existing literature to identify priority species, based on their impact on aquatic ecosystems and their associated ecosystem services, and then testing the suitability of SPOT-6 and WorldView-3 multispectral data at detecting these focal species. The priority species identified were: *Acacia cyclops* (rooikrans), *Acacia longifolia* (long-leaved wattle), *Acacia mearnsii* (black wattle), *Acacia melanoxylon* (blackwood), *Acacia saligna* (Port Jackson willow), *Eucalyptus camaldulensis* (red river gum), *Pinus pinaster* (cluster pine) and *Pinus radiata* (radiata pine). The Random Forest classifier on SPOT-6 data achieved an overall accuracy of 62.5% and this method was consequently deemed ineffective at separating invasive tree species from other tree species in the Garden Route. The overall accuracy of the WorldView-3 classifier was higher (78.9%) but the cost of the data limited the use of more images for the detection of the focal species throughout the Garden Route. Therefore, to identify priority areas for invasive tree management, criteria derived from existing literature were input into spatial conservation planning software. The analysis identified the: Saasveld section of the Garden Route National Park, the Wilderness Lakes, Knysna Forest, Knysna Estuary, Tsitsikamma Forest around Stormsriver and a disturbed area of fynbos southeast of Kareedouw as management priorities. Currently spatial conservation planning software proved to be cost-affordable and useful tool and is recommended for invasive tree management in the Garden Route.

Key words

aquatic ecosystems; ecosystem services; Garden Route National Park; invasive tree species; Southern Cape; transformer species

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List of Figures

List of Tables

List of Abbreviations

AHP	Analytic Hierarchy Process
CBA	Critical Biodiversity Area
DEM	Digital Elevation Model
EnMAP	Environmental Mapping and Analysis Programme
ENVI	ENvironment for Visualizing Images
ESA	Ecological Support Area
GPS	Global Positioning System
GRCPD	Garden Route Conservation Planning Domain
GRNP	Garden Route National Park
HGM	Hydrogeomorphic
IAP	Invasive Alien Plant
IPBES	Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
MPA	Marine Protected Area
MEA	Millennium Ecosystem Assessment
NEMBA	National Environmental Management Biodiversity Act
NFEPA	National Freshwater Ecosystem Priority Areas
NIR	Near Infra-Red
NMMU	Nelson Mandela Metropolitan University
OA	Overall Accuracy
PA	Producer's Accuracy
PECS	Program on Ecosystem Change and Society
PES	Present Ecological State
RF	Random Forest
ROI	Region of Interest
SANBI	South African National Biodiversity Institute
SANParks	South African National Parks
SANSA	South African National Space Agency
SAPIA	Southern African Plant Invaders Atlas
SCP	Spatial Conservation Planning
SPOT	*Satellite Pour l'Observation de la Terre* (lit. 'Satellite for observation of Earth')
SRTM	Shuttle Radar Topography Mission
SWSA	Strategic Water Source Areas
UA	User's Accuracy
WV	WorldView

List of Appendices

Definition of Key Terms

Acacia cyclops	Rooikrans
Acacia longifolia	Long-leaved wattle
Acacia mearnsii	Black wattle
Acacia melanoxylon	Black wood
Acacia saligna	Port Jackson willow
Aquatic ecosystem	**"**An area of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres " (Ramsar Convention Secretariat, 2013)
Ecosystem services	Goods and functions, derived from natural processes, which satisfy human needs (De Groot, 1992; Mace *et al.*, 2012)
Estuary	A body of surface water that that is permanently or periodically open to the sea and is part of a water course; where a fluctuation in water level is tidal or where the salinity is measurably higher due to the sea's influence (Ollis *et al.*, 2013)
Eucalyptus camaldulensis	Red river gum
Invasive Alien Plant (IAP)	A plant whose introduction is a result of human activity, which sustains populations over many life cycles without direct human intervention and produces large numbers of reproductive offspring, at considerable distances from parent plants. Therefore they can potentially spread over a significant area (Richardson *et al.*, 2000)
Invasive plants	Naturalised plants that produce large numbers of reproductive offspring, spreading 100 m or more in less than 50 years (Richardson *et al.*, 2000; Richardson & Rejmanek, 2004)
Pinus pinaster	Cluster pine
Pinus radiata	Radiata pine
Producer Accuracy (PA)	The number of correctly classified pixels divided by the total number of pixels that should have been in that class (Woodcock *et al.*, 2002)
Regime shift	A sudden change in the functioning of the ecosystem (Biggs *et al.*, 2012)

Region of Interest (ROI) An area within an image which represents a land use and can guide remote sensing classifications (Lillesand *et al.*, 2015)

Remote sensing Obtaining information about an object by analysing data acquired without actually coming into close contact with it, for example using satellite sensors (Lillesand *et al.*, 2015)

Riparian The zone between land and water areas, including stream and river banks and wetland edges (Gregory *et al.*, 1991)

Spatial Conservation Planning (SCP) A method to prioritise landscapes to ensure effective, long-term biodiversity conservation (Kukkala & Moilanen, 2013)

Transformer species A division of IAPs which change ecosystem conditions over a considerable area in relation to the size of an ecosystem (Richardson *et al.*, 2000)

User accuracy UA is the number of correctly classified test pixels divided by the total number of pixels in that class (Woodcock *et al.*, 2002)

Wetland "Land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil" South African National Water Act (Act No. 36 of 1998)

Zonation A type of Spatial Conservation Planning software which prioritises a landscape for conservation (Lehtomäki & Moilanen, 2013)

Chapter 1 Introduction

1.1 Introduction to ecosystem services

Ecosystem services are goods and functions, derived from natural processes, which satisfy human needs (De Groot, 1992; Mace *et al.*, 2012). The concept arose in the 1970s as 'environmental services' (Wilson & Matthews, 1970), while the current term 'ecosystem services' was conceived in the mid-1980s (Ehrlich & Mooney, 1983). The Millennium Ecosystem Assessment (MEA) The Millennium Ecosystem Assessment (MEA) indicated a need for further programs and consequently the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Program on Ecosystem Change and Society (PECS) were developed (see Platform on Biodiversity and Ecosystem Services (2016) and Program on Ecosystem Change and Society (2016) for more information). There are four main types of ecosystem services: provisioning, regulating, supporting and cultural. This includes benefits such as the provision of food, nutrient cycling and cultural value (Millennium Ecosystem Assessment, 2005b).

Aquatic ecosystems, including wetlands and estuaries, can provide a disproportionate amount of services compared with other ecosystems and are vital for human well-being (Zedler & Kercher, 2005; Vromans *et al.*, 2010). The benefits they provide include regulating the flow of freshwater and its purification (Nel & Driver, 2012) and they are particularly important in a water scarce country, such as South Africa (Ashton, 2002). However, these services are under threat when dominated by Invasive Alien Plants (IAPs).

1.2 The threat of invasive alien plants

IAPs are naturalised, non-indigenous plants that produce large numbers of reproductive offspring, which may spread 100 m or more in less than 50 years (Richardson *et al.*, 2000; Richardson & Rejmanek, 2004). These species have a competitive edge, owing to a lack of natural enemies, and thus achieve rapid growth and dispersion (Stirton, 1987). There are five general types of feedback system which drive invasion by IAPs, increasing their distribution/size and competiveness (Figure 1.1). These are changes to: fire regimes, seedbank biomass, nitrogen fixation, litter composition and soil biotic processes. These processes allow IAPs to outcompete indigenous species and change the environment (Olmstead, 2006).

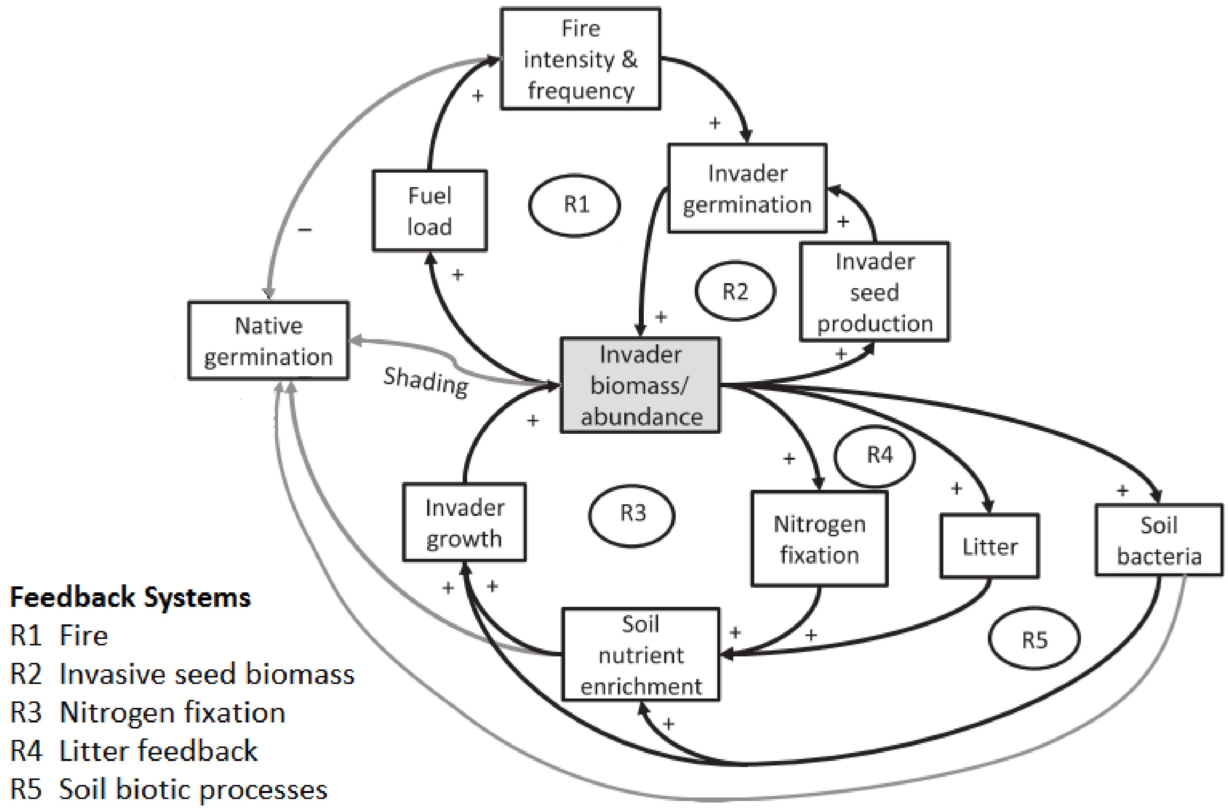

Figure 1.1. The main feedback systems which drive spread by IAPs. The most common direction for loops is shown but they can also operate in reverse. Grey arrows indicate a negative feedback system. Adapted from Gaertner *et al.* (2014).

In aquatic ecosystems, IAPs have few competitors and ample water, allowing them to thrive and outcompete indigenous aquatic ecosystem vegetation (Zedler & Kercher, 2004). The impacts of invasive trees can cause conflict of interest as they often provided useful products and services for humans (Richardson *et al.*, 2008; Van Wilgen & Richardson, 2014). Invasive tree species can be particularly damaging to aquatic ecosystems, for example by reducing their water supply (Van Wilgen *et al.*, 2008a). As trees are typically long-lived and large, they can dominate indigenous vegetation and cause changes to the structure of ecosystems (Van Wilgen & Richardson, 2014). Thus, colonisation by invasive tree species can potentially decrease aquatic ecosystem functioning, thereby leaving the habitat irreversibly damaged (Zedler & Kercher, 2005). This would be detrimental to the many ecosystem services aquatic habitats provide (McLaughlin & Cohen, 2013; Nel *et al.*, 2013). Invasive trees can also have significant impacts on the ecosystem services of the habitats they invade (Richardson & Rejmánek, 2011). They may negatively impact on water resources and biodiversity, and cause alterations to hydrology, fire regimes and nutrient cycling (Van Wilgen & Richardson, 2014). To maximise freshwater ecosystem services, invasive species must be controlled (Van Wilgen *et al.*, 1998; Ehrenfeld, 2010).

In South Africa, the value of ecosystem services is estimated to be R152 billion, however, since 2008 IAPs have caused an estimated R6.5 billion worth of loss to these services annually (De Lange & Van Wilgen, 2010).

This loss results in services having to be generated elsewhere, at a cost. For example, aquatic ecosystems are important for purifying water. Without these services, the water has to be cleaned using energy-intensive processes to be fit for human use (Trepel, 2010).

The annual budget for South Africa's IAP clearing program, Working for Water, was R600 million in 2010 (De Lange & Van Wilgen, 2010) compared with an estimated R8.4 billion for eradicating IAPs (Van Wilgen, Richardson, Le Maitre, *et al.*, 2001). As failure to implement an effective control strategy for invasive trees will result in further invasions and a clearing cost increase (Le Maitre *et al.*, 2002), prioritisation of species and areas must occur (Richardson & Van Wilgen, 2004; Hulme *et al.*, 2013). Prioritisation can happen through the application of appropriate criteria, such as defining areas vital for maintaining ecosystem services and areas most vulnerable to invasion (see Section 2.1 and 2.7.3 respectively). Defining these areas will reduce resources being misspent on invaders with minimal impact (Hejda & Pysek, 2006), ensuring that funds are applied to maximum benefit. Due to the vulnerability of aquatic ecosystems to invasive tree species and their importance for ecosystem services (Van Wilgen *et al.*, 2008a), funds should be prioritised for their protection.

1.3 Study area: The Garden Route

This section provides a background on the Garden Route, with particular focus on the Garden Route National Park (GRNP) and its importance for biodiversity and water availability in South Africa. It also covers the threat of IAPs and the management of the park.

1.3.1 Location of the Garden Route and Garden Route National Park

The Garden Route is located in the Western and Eastern Cape provinces in South Africa. It is part of the Cape Floristic Region, which is a biodiversity hotspot and covers approximately 6,100 km^2 (Figure 1.2). The area has a Mediterranean climate, is influenced by the Outeniqua mountain range to the north and the Agulhas Current of the Indian Ocean to the south (SANParks, 2010). Summer temperatures average 22 to 25 °C and winters are 18 to 21 °C (Baard & Kraaij, 2014). Rainfall varies between 500 and 1,400 mm $annum^{-1}$, with peaks in spring and autumn (SANParks, 2010). South-westerly winds are common year round but south-easterly winds dominate in summer and north to north-westerly winds are most prevalent in the autumn and winter (Tyson & Preston-Whyte, 2000).

In conservation planning, the Garden Route can be referred to as the Garden Route Conservation Planning Domain (GRCPD) (Holness *et al.*, 2010). The GRCPD consists of the Knysna and Bitou Municipalities, and parts of the George, Kou-kamma and Kouga municipalities south of the R62 Road and the Seekoei River (Holness *et al.*, 2010). Protected areas, such as Goukamma Nature Reserve, the Brenton Blue Butterfly Reserve in the Knysna Municipality and the Robberg Nature Reserve in the Bitou Municipality are also within the domain.

As the Garden Route and GRCPD are used interchangeably, data for the GRCPD can be used to represent the Garden Route. In this study, the two terms will be used synonymously.

The largest protected area located in the Garden Route is the GRNP. The park has the second highest species richness of all national parks in South Africa and its conservation is of national importance, but it also harbours many IAP species (Spear *et al.*, 2011; SANParks, 2014). The GRNP (33.80 °S 22.50 °E – 34.15 °S 24.20 °E (Baard & Kraaij, 2014)) covers approximately 1,450 km^2 (Baard & Kraaij, 2014). Its vegetation is mainly fynbos (heathlands of the Cape Floral Kingdom) and forest (SANBI, 2010a). It is divided among Wilderness, Knysna and Tsitsikamma sections and spans four local municipalities, George, Knysna, Bitou and Kou-Kamma (SANParks, 2014). It also includes an offshore area, the Tsitsikamma Marine Protected Area (MPA) covering 340 km^2 (SANParks, 2014). Many of the major rivers in the Garden Route flow through the park, including the Kaaimans, Touw, Knysna, Keurbooms, Bloukrans, Storms and Elands Rivers. The GRNP was created in 2005, it comprises the Knysna National Lake Area, the Tsitsikamma Coastal and Forest National Parks and the Wilderness National Park (SANParks, 2015). In 2011, the GRNP was expanded to include areas previously managed as State Forests (SANParks, 2010). The park is also part of important catchments for the region's irrigation and recreation (Richardson & Van Wilgen, 2004) and tourism, as it has the third highest volume of visitors of all the country's national parks (Stirton, 1987; SANParks, 2014).

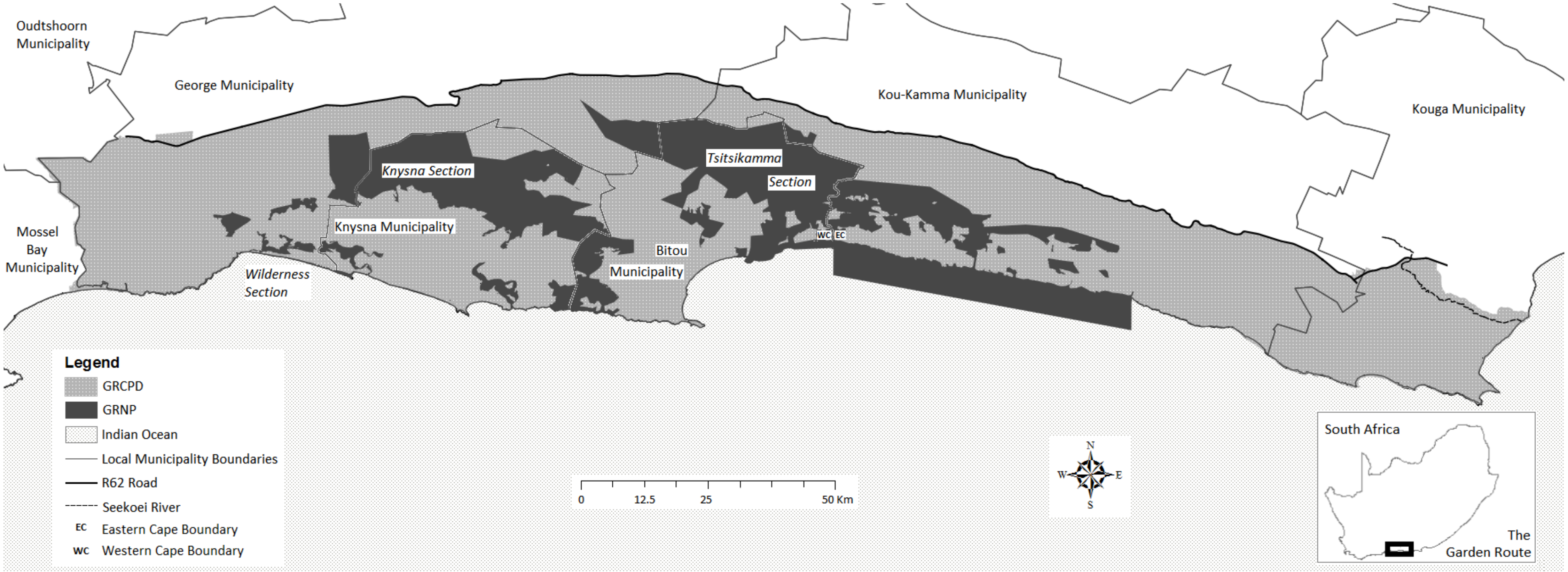

Figure 1.2. The GRNP (dark grey) in the Garden Route.

1.3.2 The Importance of protecting the Garden Route National Park for South African conservation and ecosystem services

The GRNP's unique waterways, including the Wilderness Lake System and Knysna Estuary (Figure 1.3), also make it of national and international conservation importance (SANParks, 2014). The park's aquatic systems host a great diversity of flora and fauna, some rare, including water birds and fish (Turpie *et al.*, 2002; SANParks, 2014). Several of these species are on the International Union for Conservation of Nature (IUCN) Red List, such as the Near Threatened Cape Galaxias (*Galaxias zebratus*) and Cape Kurper (*Sandelia capensis*), and the Endangered Knysna Leaf-folding Frog (*Afrixalus knysnae*) and Cape seahorse (*Hippocampus capensis*) (Department of Environmental Affairs Environmental Programme, 2015). The presence of these species indicates the importance of conserving the GRNP's aquatic ecosystems.

The park is also important for water security, with the majority being a Strategic Water Source Area (SWSA) (Nel *et al.*, 2013), and various National Freshwater Ecosystem Priority Areas (NFEPAs) fall within its boundaries (Nel *et al.*, 2011) (see Section 2.4). The area's water supply is already strained by rapid human population growth and agriculture and the influence of IAPs increases this pressure (Pauw, 2009). Due to the impacts IAPs can have on water quality and supply, wetlands and rivers are priority sites for clearing IAPs in the GRNP (SANParks, 2012).

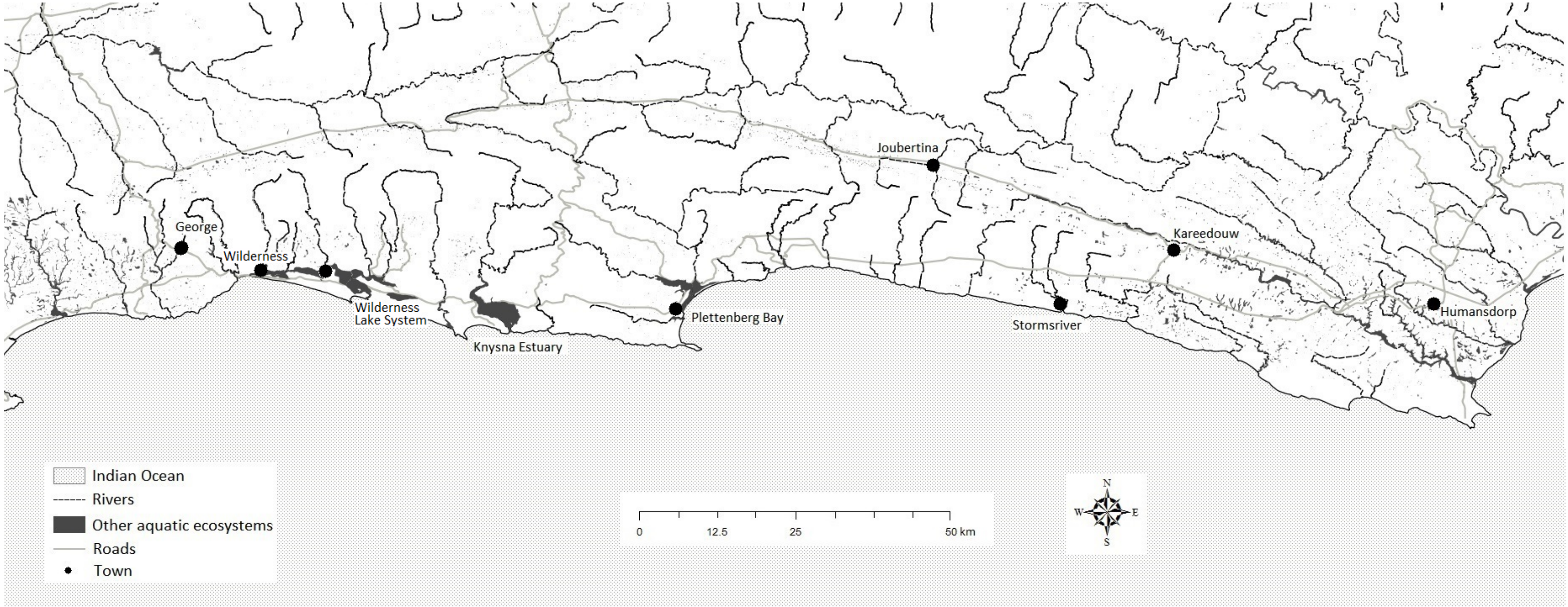

Figure 1.3. The extent of aquatic ecosystems (broken line and dark grey) and main roads (light grey lines) in the Garden Route, South Africa.

1.3.3 Invasive alien plants in the Garden Route National Park

IAPs, which are abundant in the GRNP, are considered an escalating problem and the foremost threat to the park's biodiversity (Baard & Kraaij, 2014). The area has been impacted by IAPs for over a century (Geldenhuys *et al.*, 1986) and the park's fragmented, narrow shape make it prone to edge effects and increase its vulnerability to IAPs (Baard & Kraaij, 2014). The land use surrounding GRNP, including disturbed areas and plantations, further encourages invasion. Unlike other national parks in South Africa, the GRNP has no natural barriers or fences so the many rivers, roads and entrance points facilitate IAP introduction and dispersal (Pickering & Mount, 2010).

Of the 244 IAPs Baard & Kraaij (2014) recorded in the GRNP, over half were not listed in the Southern African Plant Invader Atlas (SAPIA) for the region (Government Gazette, 2014b) and 64% were categorised as 'invaders' or 'transformers.' An invasive species is one which can spread more than 100 m in 50 years or less (Richardson *et al.*, 2000; Richardson and Rejmanek, 2004). A transformer species is an invader which causes considerable changes to its environment (Richardson *et al.*, 2000). These species therefore have the potential to significantly impact an ecosystem.

Given the significance of the problems associated with IAPs in the GRNP (Forsyth *et al.*, 2012), it is vital steps are taken to combat this issue (Vlok *et al.*, 2008). To develop a management strategy, it is necessary to identify: (a) which IAPs should be prioritised, and (b) where in the study area significant ecosystem services are being produced (see Chapter 2 for a more detailed discussion). This will allow management efforts to be focused most efficiently through prioritising the most ecologically important areas.

1.3.4 Management of the Garden Route National Park

The principal conservation objective of the GRNP is to preserve the park in a natural state without impacting biodiversity (SANParks, 2012). The current management plan for the GRNP employs the use of zonation (SANParks, 2012) which involves declaring sections for different activities, such as for ecosystem protection and tourism. The objective of zoning is to effectively manage conservation and tourism initiatives (Abell *et al.*, 2007).

To ensure these goals are met, the spatial data of the park needs to remain current (Forsyth *et al.*, 2009). Various spatial data exist (see Table 3.3) which can help with prioritisation.

1.4 Research statement

IAPs are a substantial problem in the GRNP, particularly in aquatic systems, and are a threat to regional sustainability. Owing to the cost of removal and maintenance, particular species and areas should be prioritised for management. Invasive tree species have been identified as a priority due to their negative impacts on aquatic ecosystems and water flow. A prioritisation process should be developed in which these species are located and priority areas for management identified.

1.5 Research questions

1. Which are the primary invasive species and where are they located in the aquatic ecosystems in the Garden Route?
2. What prioritisation criteria should be applied to effectively manage invasive tree species?
3. Which areas in the Garden Route invaded by invasive tree species are a management priority?

1.6 Aim

To determine which areas in the Garden Route should be prioritised for invasive tree species management.

1.7 Objectives

1. To spatially locate invasive tree species in the Garden Route.
2. To formulate prioritisation criteria for the management of invasive tree species.
3. To apply these prioritisation criteria to identify priority areas for invasive tree species management.

1.8 Chapters overview

Chapter 2 uses existing literature to demonstrate the significance of aquatic ecosystems to both water security in South Africa and other ecosystem services. It then describes the effects of IAPs on ecosystem services and why aquatic ecosystems are vulnerable to IAP encroachment. Current management of the GRNP and IAPs is discussed and previous literature and approaches to prioritising IAP management.

Chapter 3 covers the study's methods. It begins with an overview of remote sensing and the types of multispectral data available, along with the atmospheric correction process. The selection of training and test sites, the different classifiers available and accuracy assessments are also described. Finally, it explains how the prioritisation criteria were formulated and how Spatial Conservation Planning (SCP) software was used to indicate priority areas for IAP management.

Chapter 4 concerns the results of the study. This includes which tree species are a priority in the Garden Route for IAP management and the results of the Random Forest (RF) classifications on *Satellite Pour l'Observation de la Terre-6* (SPOT-6) and WorldView-3 (WV-3) multispectral data. The chapter ends with criteria for prioritising IAP management and the results of inputting these criteria into SCP software.

Chapter 5 includes a discussion of the study's results, including possible explanations for the findings and comparing them with similar research. The implications of the results for management in addressing invasive trees are then considered. This chapter also raises this study's limitations, and gives recommendations of how to address them.

Chapter 2 Literature review

This chapter addresses the importance of aquatic systems for the provision of ecosystem services and the consequent necessity of maintaining their good health. It then discusses aquatic ecosystems' vulnerability to invasive trees, and invasive tree management practices for the Garden Route National Park (GRNP) and South Africa. Existing research on invasive trees and their management is discussed and current research gaps are identified. Finally, this chapter provides a background on prioritising invasive tree management, including reviewing the relevant literature, and an approach to prioritisation.

2.1 Defining an aquatic ecosystem

The definition of an aquatic ecosystem varies (SANBI, 2009), which can be problematic for research and environmental management. For their effective management, a consistent definition is necessary. The South African National Water Act (Act No. 36 of 1998) defines a wetland as "Land which is transitional between terrestrial and aquatic systems, where the water table is usually at, or near the surface, or the land is periodically covered with shallow water and which land in normal circumstances supports, or would support, vegetation adapted to life in saturated soil." Wetlands can also be considered one of three aquatic ecosystems, the other two being rivers and open water bodies (Ollis *et al.*, 2013). However, Ramsar uses a broader definition which includes all three of these systems as wetlands. The organisation describes wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention Secretariat, 2013).

In this study, all wetland types cited by Ramsar will be included as aquatic ecosystems. This definition also encompasses the three classes of inland system, as well as estuarine systems, described by Ollis *et al.* (2013). All these ecosystem types were included due to their importance to ecosystem services (see Section 2.1 and Table 2.1). Hence, wetlands, rivers, lakes and estuaries will be included in this study, and will be collectively referred to as aquatic ecosystems. Although riparian zones can be categorised as aquatic or terrestrial systems, all riparian zones in the Garden Route will be included in this study. This is because they are important for ecosystem services (Barling & Moore, 1994), are inland systems (Ollis *et al.*, 2013) and are vulnerable to invasion by IAPs (Hood & Naiman, 2000).

Aquatic ecosystems can provide different services based on their hydrology and geomorphology. These characteristics determine how systems function and form the basis of South Africa's

Classification System for Wetlands (Ollis *et al.*, 2013). The Classification defines inland systems as "an aquatic ecosystem with no existing connection to the ocean." There are seven hydrogeomorphic (HGM) types of inland aquatic ecosystems in South Africa; rivers, channelled valley-bottom wetlands, unchannelled valley-bottom wetlands, depressions, wetland flats, floodplains and seeps (Ollis *et al.*, 2013) (Table 2.1). As estuaries are aquatic ecosystems, the services they provide are also shown.

Table 2.1. Aquatic ecosystems in South Africa; estuaries and the seven inland HGM types of wetland (Millennium Ecosystem Assessment, 2005a; Kotze *et al.*, 2009; Nel *et al.*, 2011; Ollis *et al.*, 2013).

Aquatic ecosystem classifications (Nel *et al.*, 2011)	**Description** (Ollis *et al.*, 2013)	**Associated Regulatory Ecosystem Services** (Kotze *et al.*, 2009; Millennium Ecosystem Assessment, 2005a)
Channelled valley-bottom	A wetland with a clear stream channel which lacks the features of a floodplain	Flood attenuation, erosion control, phosphate, nitrate and toxicant assimilation and sediment trapping
Depression	A basin-shaped area which accumulates surface water. This definition includes lakes	Flood attenuation and nitrate and toxicant assimilation
Estuary	A body of surface water that that is permanently or periodically open to the sea and is part of a water course; where a fluctuation in water level is tidal or where the salinity is measurably higher due to the sea's influence	Flood attenuation, erosion control, nutrient and toxicant assimilation
Flat	A wetland with minimal gradient, located on plain or bench landscapes, usually fuelled by precipitation	Flood attenuation, and nutrient and toxicant assimilation
Floodplain	A gentle-sloping, valley bottom area with characteristics such as natural levees and oxbow depressions. There is usually a net accumulation of sediment	Flood attenuation, erosion control, phosphate, nitrate and toxicant assimilation and sediment trapping
River	A wetland which connects water bodies, with clear margins and flowing water. Includes permanent and non-permanent rivers and riparian zones	Flood attenuation, nutrient and toxicant assimilation, groundwater regulation and erosion control
Seep	A wetland on a slope, dominated by uniform, gravity-driven movements of material and water	Flood attenuation, streamflow regulation, nitrate and toxicant assimilation and erosion control
Unchannelled valley-bottom	An area with an undefined channel, with a gentle slope and accumulating alluvial sediment deposits	Flood attenuation, possible stream flow regulation, erosion control, phosphate, nitrate and toxicant assimilation and sediment trapping

The Classification System for Wetlands corresponds with the South African National Wetland Map 5 (Van Deventer, 2016b), which will be used to identify the aquatic ecosystems of the Garden Route. Aquatic ecosystems were captured at a scale between 1:500 and 1:2,000 (Van Deventer, 2016b) which should be sufficient for locating aquatic ecosystems in this study.

2.2 The importance of aquatic ecosystems for ecosystem services

Aquatic ecosystems are important sources of ecosystem services, particularly those supplying freshwater. These habitats act as a filter for nutrients and pollution, as well as providing water for human, plant and animal use (Driver *et al.*, 2012). Aquatic ecosystems recharge ground water and aquifers, which helps alleviate drought impacts (Chuma *et al.*, 2012). They also regulate streamflow and help to reduce the impacts of flooding by storing flood water (McLaughlin & Cohen, 2013). These services are vital for humans' survival (Millennium Ecosystem Assessment, 2005a).

Aquatic ecosystems are essential for improving water quality (Driver *et al.*, 2012). Generally speaking, 'water quality' describes its chemical, biological and physical characteristics (Chapman, 1996). Wetlands trap sediment, and assimilate nutrients, such as nitrates and phosphates (Millennium Ecosystem Assessment, 2005a). Further benefits of aquatic ecosystems include their ability to reduce microbes and toxicants, such as heavy metals and biocides (Kotze *et al.*, 2009). These services are vital for maintaining the health of our water systems and consequently the life supported by them (Costanza *et al.*, 1997). Thus, management should concentrate its efforts towards aquatic systems, such as rivers (Van Wilgen *et al.*, 2007).

In addition to regulating water quality and supply, aquatic ecosystems provide many other services. These include providing harvestable resources, such as fuelwood, medicines and food (Millennium Ecosystem Assessment, 2005a), and maintaining biodiversity, for example by providing habitat (Vromans *et al.*, 2010). Aquatic ecosystems also help fertilise floodplains (Zedler, 2003). Due to their aesthetics and the abundance of species they support, aquatic habitats offer cultural ecosystem services, such as education, research, tourism and recreation (Kotze *et al.*, 2009). Aquatic ecosystems are important for erosion control, including the protection of river banks and coastlines (Vromans *et al.*, 2010). They also accumulate organic matter, which is vital for soil formation, and they help to regulate the climate by acting as carbon sinks (Turpie & Kleynhans, 2010). Due to the quantity and diversity of ecosystem services that aquatic systems provide, it is essential to maintain their condition to protect these services (Driver *et al.*, 2012).

Globally, aquatic ecosystems provide US$13.2 trillion worth of ecosystem services annually (Costanza *et al.*, 1997). However, this value is often overlooked when decisions regarding land use and development are made, rendering aquatic systems undervalued (Costanza *et al.*, 1997). Most of the world's aquatic systems have been degraded (Zedler & Kercher, 2005) and since 1900, at least 60% of have been lost worldwide (Davidson, 2014). Although inland aquatic systems cover a mere 3% of the Earth's surface, they account for 40% of its ecosystem services (Zedler & Kercher, 2005). In South Africa, wetlands comprise 2.4% of the land area but they provide a disproportionate amount of vital ecosystem services (Millennium Ecosystem Assessment, 2005a; Driver *et al.*, 2012). Worryingly, the country's aquatic ecosystems are being lost at a faster rate than other habitats (Driver *et al.*, 2005), with many having been destroyed or heavily degraded (Department of Environmental Affairs Environmental Programme, 2015). This loss can have knock-on impacts on ecosystem services, which then must be generated elsewhere at a cost (Costanza *et al.*, 1997).

2.3 The definition of a healthy aquatic ecosystem and how it is assessed

For aquatic ecosystems, health is a measure of changes in function from its natural state, based on changes to its hydrology, geomorphology and vegetation (Macfarlane *et al.*, 2009). A healthy aquatic ecosystem would therefore be one which is in, or is close to, it natural condition. An aquatic ecosystem has been 'lost' when it is unable to function or provide the ecosystem services that it could when it was intact (Kotze, 2004). To ensure their functioning, aquatic ecosystems in South Africa are protected by legislation, such as by the National Water Act 36 of 1998 (South African National Water Act, 1998). This has the purpose of conserving water resources, and the ecosystems and biodiversity dependent on them.

To assess the health of an aquatic ecosystem, it can be compared to its historic state or to that of a nearby, similar, un-impacted habitat (Macfarlane *et al.*, 2009). Alternatively, one can measure how well it performs certain functions (Fennessy *et al.*, 2004). For example, aquatic systems can be classified by their Present Ecological State (PES)[1]. This consists of 6 categories (A-F) describing an aquatic system's health, or ecological state (Table 2.2) (Driver *et al.*, 2012). Systems classed as A or B are presently in a good condition, those classed as C are in an acceptable state whilst systems in classes D to F are in a poor condition.

Table 2.2. The PES classes which describe the health and condition of aquatic ecosystems (Driver *et al.*, 2012).

Ecological category	Description
A	Natural and unmodified
B	Predominately natural with ecosystem functions intact. Small changes to natural habitats and biota may have occurred
C	Moderately-modified. Basic ecosystem functions are still mostly unchanged but a loss to natural habitat and biota have likely taken place
D	Largely-modified, with a large loss of natural habitat, biota and basic ecosystem functions
E	Seriously-modified, causing extensive loss of natural habitat, biota and ecosystem functions
F	Critically-modified, resulting in almost a total loss of natural habitat. Ecosystem functions may be irreversibly lost

[1] PES can also refer to Payment for Ecosystem Services

2.4 The importance of ensuring good condition of aquatic ecosystems in South Africa and the Garden Route

When aquatic ecosystems are lost or degraded, the ecosystem services they provide are impaired (Zedler & Kercher, 2005). Therefore, to conserve ecosystem services, it is necessary to conserve these habitats (Millennium Ecosystem Assessment, 2005b; Zedler & Kercher, 2005). It is estimated that half of South Africa's wetlands and estuaries have been destroyed (Vromans *et al.*, 2010). What remains are the country's most threatened ecosystems, with half of these being Critically Endangered (Driver *et al.*, 2012).

In the Garden Route, aquatic ecosystems are of high conservation importance (Department of Environmental Affairs Environmental Programme, 2015). Due to their contribution to services and their threatened status, aquatic ecosystems in the Garden Route have been protected in various ways. In the GRNP, all wetlands and rivers are designated Special Conservation Areas, meaning they have high conservation value (SANParks, 2010). The Wilderness Lake System is a Ramsar site, meaning it is a wetland of international importance (Ramsar, 2015) and all wetlands in the Garden Route are Critical Biodiversity Areas (CBAs) (Vromans *et al.*, 2010). These aquatic ecosystems should be protected in a natural or near-natural state to preserve ecosystem functioning and rare species (Holness *et al.*, 2010). Many of the Garden Route's aquatic ecosystems are National Freshwater Ecosystem Priority Areas (NFEPAs) (Nel *et al.*, 2011). An NFEPA is an area which can help meet South Africa's biodiversity goals which is to conserve 20% of freshwater aquatic ecosystems (Nel *et al.*, 2011). This highlights the importance of the Garden Route's aquatic habitats for water security (Turpie *et al.*, 2008; Nel *et al.*, 2013).

Water availability across South Africa is extremely variable, with many regions having insufficient supplies (Ashton, 2002). Countrywide, certain catchments have been classified as Strategic Water Source Areas (SWSAs). These are zones which supply a larger than average amount of surface run off to a region (Nel *et al.*, 2013). The majority of aquatic ecosystems in the Garden Route are located within the Outeniqua and Tsitsikamma SWSAs.

Only 30% of the Outeniqua SWSA and 42% of the Tsitsikamma SWSA are on protected land (Nel *et al.*, 2013), showing that water security is vulnerable. This lack of protection exacerbates the threat to the country's already stressed water supply (Ashton, 2002), which could cause a breakdown in water-based ecosystem services if proper management is not implemented (Vlok *et al.*, 2008). For example, services including the provision of freshwater and biodiversity support are under threat because of invasive tree colonisation (Le Maitre *et al.*, 2000; Van Wilgen & Richardson, 2014). Therefore, the aquatic ecosystems in the study area will require suitable management to protect the ecosystem services they provide.

2.5 The threats to aquatic ecosystems from invasive alien plants

Aquatic ecosystems in South Africa are an important source of freshwater, but there are numerous threats to their health. Agriculture, human development, climate change and IAPs have all been shown to negatively impact aquatic ecosystems (Millennium Ecosystem Assessment, 2005a). A principal threat to aquatic systems, and a leading cause of species extinction, are IAPs (Millennium Ecosystem Assessment, 2005a; Gaertner *et al.*, 2014). Wetlands and riparian zones have been extensively invaded by IAPs throughout South Africa (Richardson & Van Wilgen, 2004) and in the Western Cape, aquatic ecosystems are highly threatened by invasions (Department of Environmental Affairs Environmental Programme, 2015).

2.5.1 Why aquatic ecosystems are susceptible to invasive alien plant invasion

Aquatic habitats are more vulnerable to IAPs than other ecosystems for several reasons. Firstly, they are sinks and accumulate nutrients and sediment, which creates favourable conditions for opportunistic invaders (Zedler & Kercher, 2004). Secondly, the flow of water allows IAP seeds to be easily distributed downstream (Hood & Naiman, 2000; Le Maitre *et al.*, 2000; Zedler & Kercher, 2004). This effect is exacerbated by floods (Richardson & Rejmánek, 2011), which cause sediment deposits to accumulate and provide ideal conditions for IAPs to establish (Kercher & Zedler, 2004). The presence of moisture in aquatic ecosystems means they burn less frequently than other habitats (Le Maitre *et al.*, 2000), allowing IAPs to grow larger and outcompete indigenous species (Kotze *et al.*, 2009; Macfarlane *et al.*, 2009).

Additionally, the problems associated with IAPs may be compounded by the effects of agriculture or urban developments, with related nutrient run-off accumulating downstream, which favours the growth of aggressive invasive plant species (Zedler & Kercher, 2005). Owing to the vulnerability of aquatic ecosystems and the potential consequences of IAP invasion (Zedler & Kercher, 2004; Millennium Ecosystem Assessment, 2005a; Gaertner *et al.*, 2014), it is vital to manage IAPs in these habitats (Baard & Kraaij, 2014). This is reinforced by the importance of aquatic ecosystems for ecosystem services (see Section 2.2). Hence, efforts to control IAPs should focus on aquatic areas (Forsyth *et al.*, 2004). By protecting aquatic systems, associated ecosystem services are also protected (Millennium Ecosystem Assessment, 2005b).

2.5.2 Consequences and impacts of invasive tree invasions in aquatic ecosystems

The effects of IAPs in aquatic systems are varied, but high levels of water consumption by some IAPs, compared with indigenous species is a major threat to aquatic ecosystems. In particular, invasive woody plants can retain high volumes of water (Le Maitre *et al.*, 2000) as they have higher evapotranspiration rates than native flora (Scott, 1999). This can reduce the provision of freshwater when dense stands develop. Common invasive tree species of South Africa include *Pinus* species (pines), *Eucalyptus* species (gum trees or eucalypts) and *Acacia*s, commonly known as wattles or Acacias (Le Maitre *et al.*, 2000; Van Wilgen *et al.*, 2007).

Since the 1800s in South Africa, commercial plantations of wattles, pines and gum trees have provided many harvestable products (Van Wilgen *et al.*, 2001a; De Wit *et al.*, 2002) and have proliferated (Baard & Kraaij, 2014). Inevitably, some seeds dispersed into the surrounding habitat, resulting in the steady degradation of the region's ecosystems (Turpie *et al.*, 2008). Success of plant invasions can be attributed to a lack of parasites in South Africa (Hierro *et al.*, 2005), the climatic conditions being similar to that of their native land and the plants' ability to produce numerous, persistent seed banks (Milton, 1980).

Invasive trees can cause negative impacts on aquatic ecosystems. *Acacia mearnsii* (black wattle) and *A. melanoxylon* (blackwood), create dense thickets and impair ecosystems' function (Dye & Jarmain, 2004; Baard & Kraaij, 2014), whilst *Eucalyptus camaldulensis* (red river gum) is suited to invading riparian zones (Tererai, 2012). These invasive species can reduce water supply, an issue which is of particular concern in a water stressed country (Le Maitre *et al.*, 1996, 2016). Downstream of invasions, the subsequent reduction of freshwater availability can lead to degradation of aquatic ecosystems (Zedler & Kercher, 2005; Kotze *et al.*, 2009).

Invasive tree species also reduce water quality. Species such as Acacias can cause eutrophication, thereby worsening South Africa's poor water quality problem (Driver *et al.*, 2012). The higher levels of nutrients produced by invasive tree species through excessive littering, stimulate the growth of algae in freshwater systems (Jovanovic *et al.*, 2009; Chamier *et al.*, 2012). The death and subsequent decomposition of these algae in large numbers reduces the oxygen content of water. This can render some water layers anoxic, resulting in the death of fish and other disruptions to aquatic ecosystems (Zedler & Kercher, 2005).

Invasive trees can also impact on soil conditions. *Acacia, Eucalyptus* and *Pinus* species are inefficient at binding soil, which can cause soil erosion (Kotze *et al.*, 2009). These species can release volatile compounds (Chamier *et al.*, 2012) and increase water repellency of the soil (Scott, 2000). Increased repellency can reduce the stability of river banks, resulting in erosion (Le Maitre *et al.*, 2014). This can lead to a reduction in water quality (Kotze *et al.*, 2009).

Invasives can also alter soil chemistry by increasing nutrient levels (Jovanovic *et al.*, 2009). For example, Acacias can produce greater amounts of nitrogen than indigenous vegetation, which then gets leached into the soil when the plants die and decay. Increased nitrogen lowers the pH of the soil, making conditions unfavourable for indigenous species. These altered conditions encourage the growth of species which can tolerate increased acidity (Tererai, 2012), such as nitrophilous IAPs (Yelenik *et al.*, 2004) and invasive grass species (Gaertner *et al*., 2014).

Invasive trees can have negative impacts on native aquatic flora. Acacias, pines and eucalypts can reduce biodiversity of indigenous plant communities by outcompeting native species (Le Maitre *et al.*, 1996; Holmes & Cowling, 1997a; Gaertner *et al.*, 2014). This can lead to local extinctions of indigenous species, loss of ecosystem functioning and a reduction in ecosystem services (Holmes and Cowling, 1997b). The colonisation by invasive tree species can cause a feedback loop, by reducing species richness, which increases the vulnerability of aquatic ecosystems to further IAP invasion (Zedler & Kercher, 2004; Gaertner *et al.*, 2014) (see Figure 1.1).

Woody plantation species are a conundrum in South Africa (Richardson, 1998). Invasive trees, such as *Acacia, Eucalyptus* and *Pinus* species, have commercial value for forestry (Dennill & Donnelly, 1991; Wingfield *et al.*, 1996; McConnachie *et al.*, 2015), which needs to be evaluated against the potential negative environmental impacts these species can cause. Thus, an effective management plan needs to take both of these into account.

2.6 South African legislation regarding the control of invasive alien plants

Since the National Environmental Management Biodiversity Act (NEMBA) was promulgated in 2004 (Act No. 10 of 2004), organisations responsible for protected areas, are obliged to control IAPs, reducing them to a manageable density (SANParks, 2012). NEMBA provides a framework for conserving South Africa’s natural resources and, to a large extent, dictates the IAP management plan for the GRNP (Vromans *et al.*, 2010). The Act lists the species requiring control, dividing them into four categories (Table 2.3). The highest priority IAP species in South Africa are classed as 1a or 1b. These classifications can provide a foundation for an IAP control strategy.

Table 2.3. The NEMBA categories for IAP management (Government Gazette, 2014a).

Category	Description
1a	Must be controlled
1b	Must be controlled and may require Government assistance to remove
2	Permit required to keep
3	Allowed but their spread must be contained Category 3 species in riparian zones are deemed category 1b

2.7 Prioritising invasive tree species management

Previous literature has highlighted the importance of controlling invasive tree species, especially in areas important for freshwater supply (see Sections 2.3 and 2.5). To do this, prioritisation criteria must be developed. For landscapes, this process includes a literary review which focuses on the Garden Route and, specifically, aquatic ecosystems. To manage invasive trees, the species responsible for the worst environmental impacts, known as transformer species, must be identified.

2.7.1 Previous studies prioritising invasive alien plant management in South Africa

Prioritisation for IAP management involves ranking a consideration above another so it becomes more important (Rountree *et al.*, 2009). The process is essential for an effective strategy (Forsyth *et al.*, 2009). Several studies have developed prioritisation criteria for managing IAPs and those which produced ranked criteria, which are applicable to this study, are shown in Table 2.4.

Table 2.4. Criteria ranking and their weightings for prioritising management of IAPs across a landscape. Sub-criteria are shown in brackets if the weight is greater than the next highest ranking criteria. The percentages are the weightings given by the authors.

Study	Study area	Highest ranking criteria	2nd highest ranking criteria	3rd highest ranking Criteria
Forsyth *et al.* (2015)	GRNP	Conservation and biodiversity importance (threat status) 29.47%	Conservation and biodiversity importance (special conservation areas*) 26.34%	Value of the land for water production 25.62%
Forsyth *et al.* (2012)	Western Cape	Ability of an area to hold onto gains made once it has been cleared of IAPs 42.4%	Potential for IAP control to contribute to water resources 22.3%	Threat from priority IAPs 17.3%
Forsyth & Le Maitre (2011)	GRNP	Biodiversity value of the land 26.6%	Tourism use zones 15.3%	Impact on socio-economic risk 15.1%
Forsyth *et al.* (2009)	Western Cape	Ability of an area to hold onto gains made once it has been cleared of IAPs 49.1%	Value of land for biodiversity conservation 18.1%	Current extent of invasion 12.3%
Van Wilgen *et al.* (2008a)	Fynbos biome	Value of the land (for water) 45.7%	Value of the land (conservation importance) 20.9%	Presence of priority IAPs 14.3%
Van Wilgen *et al.* (2007)	Rivers in South Africa	Four criteria specified without weightings. There are: Current distribution of IAPs in rivers, Potential IAP distribution in rivers, Degree of water stress in rivers and Largest habitat loss in rivers		

* Defined as CBAs (Holness *et al.*, 2010)

2.7.2 Prioritising transformer plants for invasive tree species management

A possible start to determining which areas are most under threat from invasive tree species in the Garden Route is through identifying the most problematic invasive tree species. These species could then be prioritised for management (Driver *et al.*, 2012). This would mean identifying those invasive tree species with a high negative environmental impact, particularly on ecosystem services. Invaders which change the condition or functioning of the ecosystem are known as transformer species (Richardson *et al.*, 2000; Levine *et al.*, 2003; Vilà *et al.*, 2011). Transformer species are able to outcompete indigenous species (Olmstead, 2006) and can also cause regime shifts, i.e. a sudden change in the functioning of an ecosystem (Biggs *et al.*, 2012).

Examples of regime shifts are shown in Table 2.5 (see also Figure 1.1 and Section 2.5.2). These changes can be difficult to predict (Walker *et al.*, 2004) and make it problematic for feedback systems to return ecosystems to their previous regime (Scheffer *et al.*, 2001). This can cause a loss of ecosystem services, which could adversely impact human well-being (Crépin *et al.*, 2012). Because effective management can reduce the risk of regime shifts, controlling transformer species should be a priority for management (Crépin *et al.*, 2012; Gaertner *et al.*, 2014). The term 'transformer' will be used to describe species which cause regime shifts, in accordance with Richardson *et al.* (2000).

Although Henderson (2001) provided an extensive list of transformer species, this was at a national scale and may not always be applicable to the Garden Route. Therefore, for this study, the transformer species in the GRNP listed by Baard & Kraaij (2014) was used instead.

Table 2.5. Criteria for defining a transformer plant species. Taken from Richardson *et al.* (2000) unless otherwise stated.

Category of transformer plant	Example	State shifted from	State shifted to
Excessive resource (e.g. light, nutrients water, oxygen) user	Excessive water user *Acacia mearnsii*	Fynbos	Ecosystem dominated by *Acacia mearnsii* (Van Wilgen *et al.,* 2008b)
	Excessive light user *Pinus pinaster*	Fynbos	Species richness is reduced (Richardson *et al.*, 1989)
Donor of limiting resources	Nitrogen donor *Acacia* spp.	Fynbos	Landscapes invaded by nitrophilous invaders (Yelenik *et al.*, 2004)
Fire promoter or suppressor	Fire promoter *Acacia* spp.	Fynbos	Ecosystem dominated by *Acacia* spp. (Van Wilgen & Richardson, 1985)
	Fire suppressor *Mimosa pigra*	Shrubland	Invader-dominated ecosystems with an altered fire regime (Brooks *et al.*, 2004)
Promotors of erosion	*Pinus* spp. (Van Wilgen *et al.*, 2007)	Riparian habitat	Increased sediment deposition favouring the growth of invasive species (Hood & Naiman, 2000)
Sand stabiliser	*Acacia cyclops* (Henderson, 2001)	Un-vegetated sand dunes	Vegetated sand dunes
Sediment stabiliser (e.g. coloniser of intertidal mudflats)	*Rhizophora mangle*	Tidal wetland	Vegetated tidal wetlands
Litter accumulators	*Eucalyptus* spp.	Fynbos	Invader-dominated ecosystems with excessive amounts of litter
Salt accumulators or redistributors	*Tamarix* spp.	Riparian habitat	Monocultures (Brock, 1994)

2.7.3 The significance of disturbed habitats for prioritising invasive tree species management

To predict areas of transformer species colonisation, it is necessary to identify which areas within a landscape are most susceptible to invasion by these plants (Van Wilgen *et al.*, 2007; Forsyth & Le Maitre, 2011; Forsyth *et al.*, 2015). Disturbance is considered to disrupt natural processes, thereby reducing an ecosystem's ability to perform ecosystem services (Macfarlane *et al.*, 2009). Therefore a disturbed habitat is one that has been altered from, but still resembles, its natural state (Baard & Kraaij, 2014). This includes roadsides, rivers, plantation boundaries and main footpaths (Parendes & Jones, 2000; Alston & Richardson, 2006; McConnachie, Cowling, Van Wilgen, & McConnachie, 2012; Baard & Kraaij, 2014; McConnachie *et al.*, 2015). Disturbed areas are highly vulnerable to invasion (SANParks, 2014; Forsyth *et al.*, 2015) and aquatic ecosystems can easily become disturbed (Zedler & Kercher, 2004). Disturbed habitats typically have higher numbers of IAP species than undisturbed areas and are more vulnerable to invasion (Hobbs & Huenneke, 1992; Baard & Kraaij, 2014). This can be due to the disturbance triggering the release of large seed banks, as with *Acacia* species, allowing the invaders to dominate over natural flora (Le Maitre *et al.*, 2011). As disturbed areas can also facilitate the spread of IAPs (Hobbs & Huenneke, 1992; Zedler & Kercher, 2004), awareness and monitoring of these sites should be a management priority (Baard & Kraaij, 2014).

Like disturbed areas, transformed habitats (areas which have lost their structure and original function) are also highly susceptible to invasive tree species (Baard & Kraaij, 2014). However, their ecological value has been highly compromised (Macfarlane *et al.*, 2009) and the effort and resources necessary for their restoration may be too great (Rountree *et al.*, 2009). For this reason, they were not included as a management priority in this study. As aquatic ecosystems have been identified as a priority, the focus should be on moderately degraded areas, as pristine aquatic ecosystems do not need restoration (Rountree *et al.*, 2009).

2.8 Research gaps

2.8.1 Research gaps in the identification of invasive tree species and their distribution in the Garden Route

In the Garden Route, there is disagreement among researchers over prioritisation of invasive tree species, resulting in different recommendations (see Table 4.2). Several studies in South Africa have created criteria for identifying transformer tree species (Forsyth & Le Maitre, 2011; Gaertner *et al.*, 2014) or listed plant species based on their environmental impact (Baard & Kraaij, 2014), but no known research has focused on aquatic ecosystems, despite the vulnerability of these areas to invasive trees and their importance for ecosystem services. Consequently, an appropriate strategy to deal with the issue of IAPs in aquatic ecosystems is required (Forsyth & Le Maitre, 2011).

Although several studies note the importance of actively managing areas with a presence of priority species (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2009, 2012; Forsyth & Le

Maitre, 2011), they do not identify these areas within their study areas. The latest IAP distribution data were published by Kotzé *et al.* (2010). The data were only able to identify the three dominant IAP species in each 100 m^2 plot sampled using aerial surveys, meaning the application at a local (quaternary catchment) level is limited. The GRNP is in need of updated techniques to effectively monitor the threat of IAPs (Baard & Kraaij, 2014) and a spatial database of IAP distribution at a local level is recommended for the area (Forsyth *et al.*, 2009).

Owing to the size of the Garden Route, fieldwork locating priority invasive tree species would be time consuming with limited access to steep slopes. Remote sensing is therefore a suitable alternative (Hestir *et al.*, 2008). For multispectral data to be able to remotely sense invasive trees, the resolution must be sufficient. Thus, the canopy size of focal tree species must exceed the pixel size of the data. This means that the canopy size of priority invasive tree species, and the appropriate spatial data for identifying them, needs to be investigated.

2.8.2 Research gaps in prioritisation criteria for invasive tree management in the Garden Route

To gauge the most appropriate IAP management sites, several studies have identified prioritisation criteria (see Table 2.4). However, owing to the differing dates, objectives and study sites, there are dissimilarities concerning which criteria are most appropriate for the Garden Route. Although these prioritisation studies stated the significance of water in managing IAPs (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2009, 2012, 2015; Forsyth & Le Maitre, 2011), the relative importance of this criterion to others was disputed (see Table 4.7). Several studies included social criteria, such as job creation opportunities (Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2012), however such values can sometimes conflict with ecological criteria (McConnachie *et al.*, 2012). These findings suggest objectives in prioritising IAPs in aquatic systems need to be clarified, with a focus on environmental considerations.

Several studies noted the importance of controlling IAPs in areas of value for water, such as aquatic ecosystems (Forsyth *et al.*, 2012, 2015; Baard & Kraaij, 2014). Yet, at a local scale, aquatic ecosystems are underrepresented using spatial data (Van Deventer et al., 2016). Studies also note the importance of areas particularly susceptible to invasion by IAPs (Van Wilgen *et al.*, 2007; Forsyth & Le Maitre, 2011; Forsyth *et al.*, 2015). However, none of these studies identified where these areas were. Forsyth *et al.* (2015) excluded disturbed areas (as defined by SANBI (2010d)) in their management priority maps as no fine scale data were available to pinpoint these areas. These findings indicate a lack of spatial data for the purpose of prioritising invasive tree management.

2.8.3 Research gaps in the application of prioritisation criteria

Traditionally, the Analytic Hierarchy Process (AHP) (Saaty, 1990) has been used to create weighted prioritisation criteria for IAP management (Forsyth *et al.*, 2009; Le Maitre *et al.*, 2012). An advantage of AHP is its interactivity, which allows management to easily explore the implications of changing the criteria's weights (Forsyth *et al.*, 2009). Several studies applied their AHP results to the Garden Route (Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2009, 2012; Forsyth & Le Maitre, 2011), however, the results are not always applied spatially to produce a map of priority areas (Van Wilgen *et al.*, 2008a; Forsyth & Le Maitre, 2011). This can partly be attributed to a lack of appropriate spatial data to represent the criteria (Forsyth *et al.*, 2009).

One approach has been to divide the landscape into priority quaternary catchments (Van Wilgen *et al.*, 2007; Forsyth *et al.*, 2009, 2012) or priority management compartments (Forsyth *et al.*, 2015) based on the derived criteria. A drawback of this method is that it does not fully incorporate the connectivity of the landscape as it does not account for variables which extend beyond these boundaries or factors which can impact several compartments). (Lehtomäki *et al.*, 2009; Delavenne *et al.*, 2012). The suitability of an approach for implementing prioritisation criteria which is at scales finer than an entire catchment should therefore be investigated.

The Garden Route is large, thus, implementing a prioritisation strategy could prove problematic. Spatial Conservation Planning (SCP) software has not been widely used in the Garden Route, but it could prove to be a suitable tool for this task. The results of remotely sensing invasive trees can be included in an SCP analysis, which may potentially identify the areas which should be prioritised for IAP management.

Chapter 3 will describe the methods in detail.

Chapter 3 Methods and materials

This chapter discusses how priority Invasive Alien Plants (IAPs) were identified and remotely sensed. It includes descriptions of the types of multispectral data available, the atmospheric correction process, the selection of training and test sites, the different classifiers available and accuracy assessments. It then describes how the prioritisation criteria for managing landscapes were formulated. The rest of the chapter explains how the derived prioritisation criteria and spatial data were inputted into Spatial Conservation Planning (SCP) software to highlight priority areas for IAP management. The list of focal invasive tree species and the weightings of the chosen prioritisation criteria are shown in Chapter 4 (Tables 4.2 and 4.6 respectively).

3.1. Identifying priority species for invasive alien plant management using existing data

Owing to the number of IAPs in the Garden Route and their varying impacts on aquatic ecosystems (see Section 2.5.2), priority species have to be identified. To be a priority in this study, a species had to: a) be a tree (Van Wilgen *et al.*, 2008a), b) be a transformer (Baard & Kraaij, 2014) and c) invade aquatic ecosystems (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008b; Forsyth *et al.*, 2012). A decision tree for the process of identifying the priority species is shown in Figure 3.1 (see Section 4.1 for a description of the criteria and the results of their application to the Garden Route). Only tree species were included as they typically have the worst impacts on aquatic ecosystems (see Section 2.5.2). Studies undertaken at a national level, such as Robertson *et al.* (2003), were omitted because many of the species identified as a priority have not invaded the Cape Floristic Region. However, studies which concentrated on IAPs that invaded aquatic ecosystems or species that transpired excessively were included.

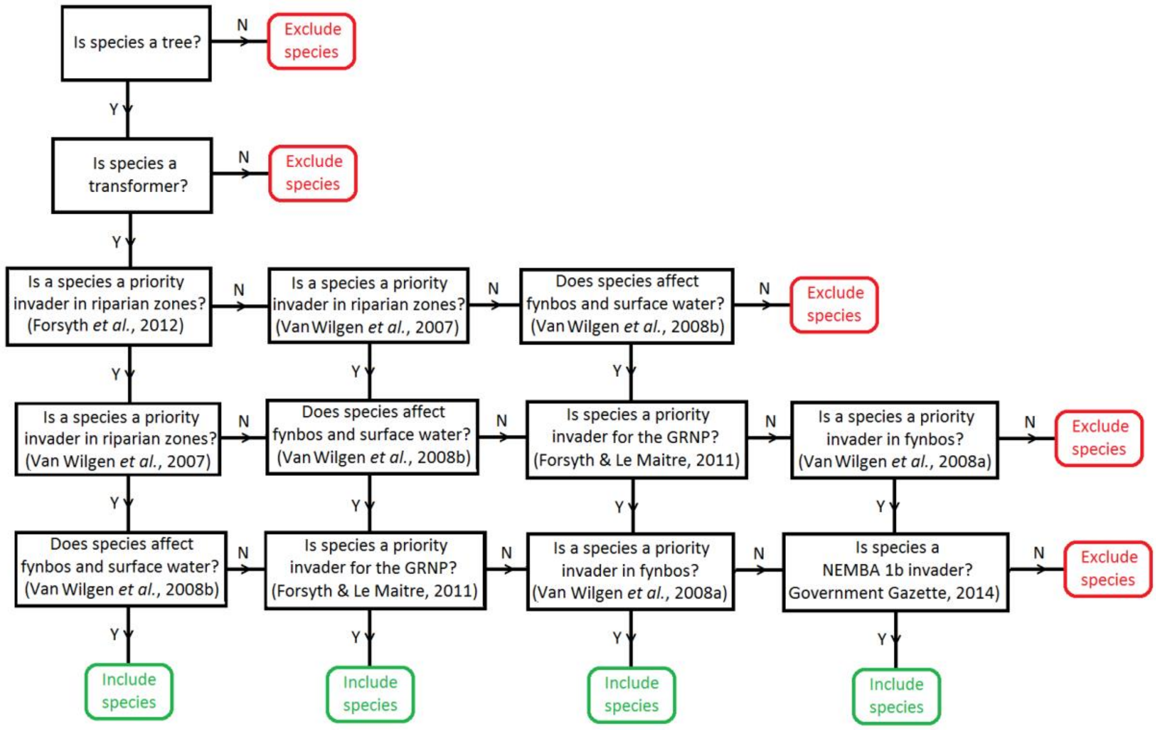

Figure 3.1. The decision tree for evaluating if a species should be a priority for invasive tree management in the Garden Route. Any species listed in one of the prioritisation studies (see Table 4.2) was checked using this method, starting by asking if it is a tree, to evaluate its appropriateness as a priority for this study. After Zimmerman *et al.* (2011).

Eight species in three genera (*Acacia, Eucalyptus* and *Pinus*) met the requirements for this study, namely: *Acacia cyclops* (rooikrans), *A. longifolia* (long-leaved wattle), *A. mearnsii* (black wattle), *A. melanoxylon* (blackwood), *A. saligna* (Port Jackson willow), *Eucalyptus camaldulensis* (red river gum), *Pinus pinaster* (cluster pine) and *P. radiata* (radiata pine) (see Table 4.2 for a list of all considered invasive tree species). After selecting these species, they could then be detected in the study area through remote sensing.

3.2 The use of existing spatial data for land management

To identify aquatic ecosystems for the classification, shapefiles were obtained of the South African National Wetland Map 5 (Van Deventer, 2016b). The rivers were buffered by 30 m each side to represent riparian zones (Le Maitre *et al.*, 2000). Drainage and source areas of the Garden Route Vegetation data (SANBI, 2010a) were merged with these data. This produced a layer containing aquatic ecosystems in the study area, the majority of this layer being riparian wetlands. The total area for aquatic ecosystem in the Garden Route was 264.32 km^2.

The National Invasive Plant Survey (SANBI, 2010b) provided data on known locations of wattles, gum trees and pines. These data were intended to guide capturing Regions of Interest (ROIs) for these species, however they could not be used because the data contained different genera of plants which were not separable at species level and no point data were available (Kotzé, 2016) (see Section 3.4.3 for more information on ROIs). Instead, these data were used to indicate high density areas of the focal invasive tree species.

These sites were visited and the trees' location captured with a Global Positioning System (GPS) (see Appendix 1 for the coordinates and description of each site). Sites nearby to rivers, roads and plantations were favoured, as these are disturbed habitats which typically harbour more invasive trees (Hobbs & Huenneke, 1992; Baard & Kraaij, 2014) (Figures 3.2, 3.3 and 3.4). Polygons of the invasive tree canopies were digitised to indicate the extent of larger canopies of the focal species. The training and test sites were then captured in these polygons.

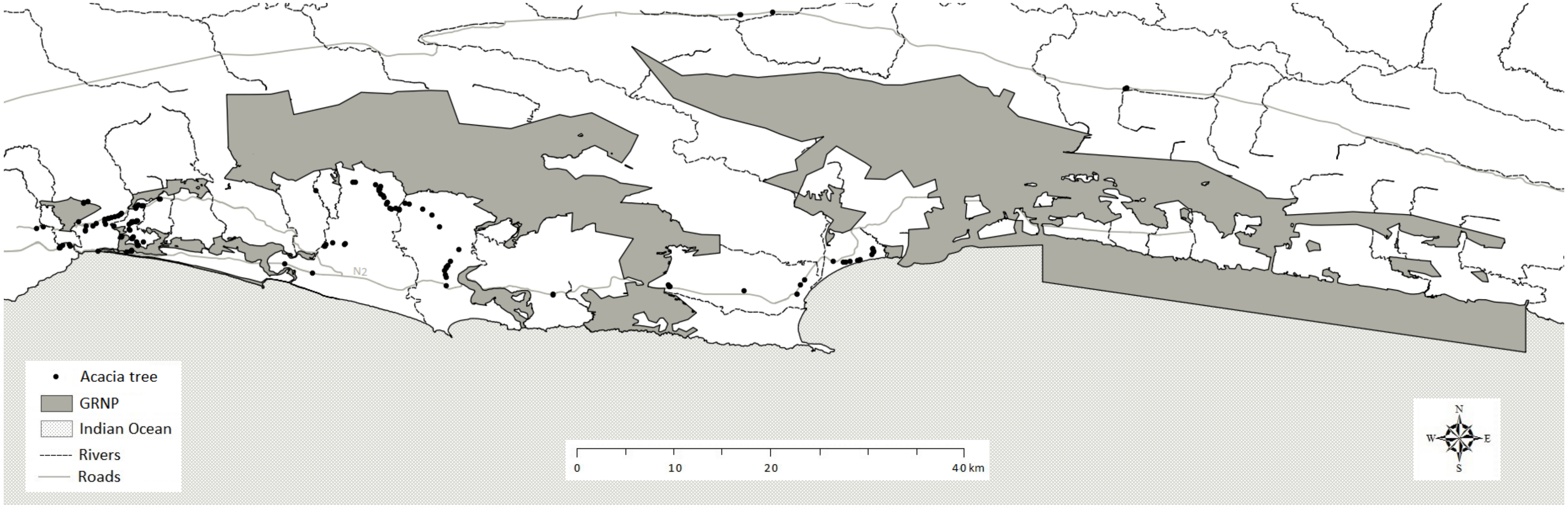

Figure 3.2. The location of the GPS points for the *Acacia* trees (black dots) in the Garden Route obtained for this study.

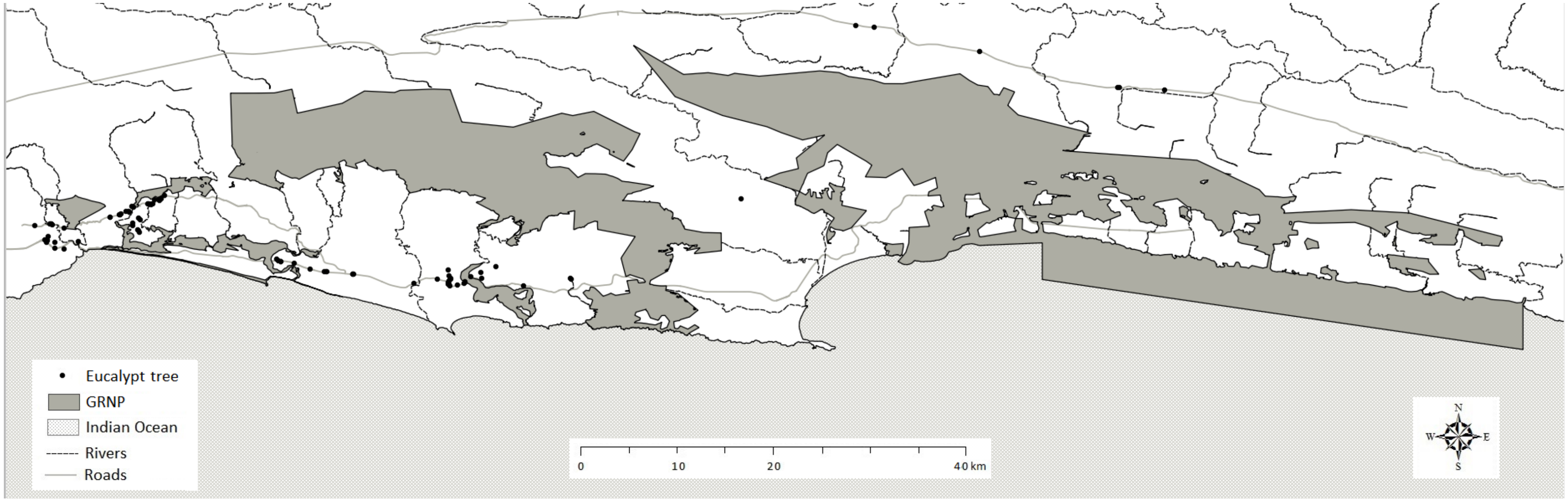

Figure 3.3. The location of the GPS points for the *Eucalyptus* trees (black dots) in the Garden Route obtained for this study.

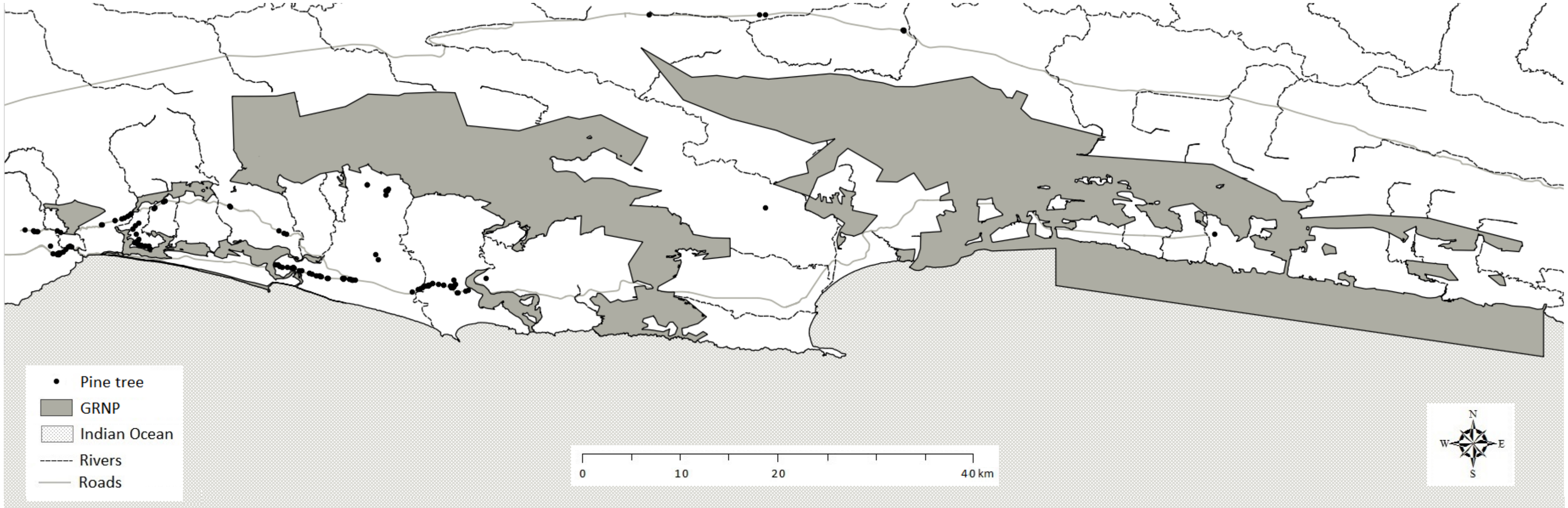

Figure 3.4. The location of the GPS points for the *Pinus* trees (black dots) in the Garden Route obtained for this study.

Various spatial data were used to guide the capturing of land classes for the classifications. The shapefile for the Garden Route Conservation Planning Domain (GRCPD) was used and data were clipped to this as required. To indicate land classes, two datasets were primarily used: the Vegetation layer (SANBI, 2010a) and Transformation layer (SANBI, 2010c) (see Table 3.3 for the dates and resolution of these data sources). The Farm, Plantation and Urban classes of the Transformation data were extracted and merged with the Vegetation layer (SANBI, 2010a).

The Dune and Grassland classes were not used, despite being part of the Vegetation layer, because neither class would have produced a spectral signature not subject to edge effects. Moreover, the Grassland class only covered a small area and was mixed with agricultural land. The Dune class had a narrow distribution and was influenced spectrally by the waves of the Indian Ocean. The data from the Vegetation and Transformation layers were overlaid with the aquatic ecosystems and invasive tree data (described in Sections 3.2.1 and 3.2.2). These data were then used to guide the capturing of ROIs (see Section 3.4.4).

3.3 The multispectral data available for this study

3.3.1 Introduction to remote sensing and multispectral data

Remote sensing is the process of obtaining information about an object without coming into close contact with it, for example using satellite sensors (Lillesand *et al.*, 2015). Considering the extent of the Garden Route and the difficulty in accessing the mountainous and aquatic terrains, remote sensing was considered more time and cost effective than field work.

Classifications of multispectral data can be influenced by various factors which reduce their accuracy. The images are prone to atmospheric and environmental effects including cloud cover and changes in slope, season, illumination and moisture (Lillesand *et al.*, 2015). The growth stage and reflectance properties also influence the ability of multispectral data to separate species from one another. This means the same species can produce diverse spectral responses and different species can have similar spectra (Xie *et al.*, 2008). Growth beneath the canopy may also be difficult to detect (Adam *et al.*, 2010). These issues can reduce the accuracy of a remote sensing classification.

3.3.2 The suitability of SPOT-6 data at identifying invasive tree species in the Garden Route

The South African government, through the South African National Space Agency (SANSA), routinely acquires *Système Pour l'Observation de la Terre* (SPOT) data which are freely available for research. The SPOT-6 data have a 6 m spatial resolution and comprise four multispectral bands in the: blue (0.450-0.520 µm), green (0.530-0.590 µm), red (0.625-0.695 µm) and Near Infra-Red (NIR) (0.760-

0.890 µm) ranges of the electromagnetic spectrum. There is also a panchromatic band with a 1.5 m resolution (0.450-0.745 µm) (Astrium, 2013). Although hyperspectral and multispectral data with more bands can produce higher classification accuracies, such data is often costly and has limited availability (Immitzer *et al.*, 2012).

For this study, SANSA provided four SPOT-6 images covering the Garden Route from April 2013 to October 2015. Images less than a year old were preferable, due to the rate of spread of IAPs (Rowlinson *et al.*, 1999). However, cloud cover in recent data meant, in certain areas of the Garden Route, SPOT-6 data from 2013-14 was the most recent and suitable (Table 3.1). The SPOT-6 data did not cover the entire extent of the Garden Route but all available and suitable data were used. The total area was approximately 6,700 km² as, in certain directions, the data extended beyond the boundary of the Garden Route (which was defined in this study using the boundary of the GRCPD).

Table 3.1. The acquisition times and dates of the SPOT-6 data covering the Garden Route. The letters A-D correspond with four SPOT-6 images shown in Figure 3.6.

SPOT-6 Images	Acquisition date	Time (GMT)
A	04/04/2014	08:04
B	20/03/2015	08:04
C	22/04/2013	08:16
D	01/06/2013	08:08

In the Western Cape, on the Klein Swartberg Mountain in the Overberg district, SPOT-6 has been used to successfully separate isolated canopies of *Pinus* species with an overall accuracy (OA) of 84% (Forsyth *et al.*, 2014). The researchers used a supervised classification to identify *Pinus* and non-*Pinus* sites, followed by ground-truthing random sites to ensure accuracy. However, the only tree species in their study area were *Pinus*. In the Garden Route, *Pinus* and other invasives are often mixed with indigenous forest. Nevertheless, the Forsyth *et al.* (2014) study suggests that the focal tree species can be mapped using medium resolution data, such as SPOT-6.

3.3.3 The suitability of multispectral data for identifying invasive tree species in the Garden Route

The ability to map invasive tree species with remote sensing requires a sensor with suitable spatial and spectral resolution. Detection by sensors is dependent on the canopy size of the tree and whether a species typically grows singularly or in clusters. Multispectral sensors can have difficulty classifying clusters of trees consisting of different heights, stands with low densities and canopies smaller than the size of sensors' pixels (Immitzer *et al.*, 2012). However, the accuracy can be improved when used with ground truthing (Forsyth *et al.*, 2014). Nonetheless, appropriate multispectral data must be used to successfully detect focal invasive tree species.

A visual inspection of the canopies of the focal invasive tree species were done in Google Earth (Google Inc, 2015) revealing that they were predominantly isolated canopies with a range of between 2-3 m in diameter. Only a few of the canopies were therefore suitable for use in the image classification using the SPOT-6 data. Owing to the distribution of the focal tree species across the Garden Route and the images stemming from different dates, two classifications were attempted using the SPOT-6 data. An initial classification was done using all four SPOT-6 images A-D, representing 6,700 km². This classification was expected to produce poor results owing to the differences in illumination and atmospheric conditions across the four time periods of the imagery. A second classification was therefore attempted using only Image A (1,585 km²), where a number of the focal tree species with sufficient diameters in canopies occurred. The classification was expected to show an improvement for this image because of the size and number of end members.

Image A covered George and Wilderness (see Figure 1.3) and will therefore be referred to as the (SPOT-6) classification of the George and Wilderness area. The initial SPOT-6 classification of the Garden Route will be referred to as such. The classification of the George and Wilderness area only used Image A because this section contained the largest identified invasive tree canopies of the four SPOT-6 data.

In additional to the SPOT-6 images, WorldView-3 (WV-3) was deemed suitable for locating the focal species as it regularly covers the Garden Route and has a higher spatial resolution than SPOT-6. Given the capabilities of WV-3, Digital Globe was contacted to request a sample to evaluate the data's suitability for mapping the focal tree species within the study area. A free sample was obtained for the extent of 25 km² within a section of SPOT-6 Image A dating to 25 August 2015 at 08:53 GMT (Figures 3.5 and 3.7). The WV-3 data consist of a 0.31 m panchromatic and eight 1.24 m multispectral bands: red, red edge, coastal, yellow, green, blue, NIR and NIR2 (Satellite Imaging Corporation, 2016). The red edge band in multispectral data has been shown to improve separation of tree species and therefore WV-3 data have the potential to achieve higher accuracies than SPOT-6 (Cho *et al.*, 2015). The yellow band should enable the identification of eucalypt and wattle flowers (Milton, 1980; Henderson, 2001), hence the request for spring or summer (August to November) images.

Figure 3.5. The extent of the WV-3 data (broken lines) obtained from Digital Globe for the purposes of classifying invasive tree species the Garden Route.

Immitzer *et al.* (2012) were able to classify ten tree species, including *Pinus spp.*, in Austria with an OA of 82% and concluded that WV data have high potential for invasive tree mapping. A study in South Africa using WV-2 classified, with over 85% accuracy: *Acacia mearnsii*, *Eucalyptus grandis*, *E. nitens*, *E. smithii*, *Pinus elliotii* and *P. patula* (Peerbhay *et al.*, 2013). Thus, this implies WV data are suitable for identifying wattles, gum trees and pines and may therefore be able to separate invasive tree species in the Garden Route too.

3.4 Classifying remotely sensed data

Atmospheric effects can impact on remote sensing classification (Elmahboub *et al.*, 2009), meaning that SPOT-6 and WV-3 data both required correction. The software ATCOR-2 (Richter and Schläpfer, 2014) was used for atmospheric correction because the majority of the study area was flat or gently sloping. ATCOR-3, which is for very mountainous terrain, was not considered suitable as most of the mountainous areas did not show severe impacts of shadow. The reference spectra classes used for atmospherically correcting the images can be found in Appendix 1. After correction, the SPOT-6 data were mosaicked (Figure 3.6).

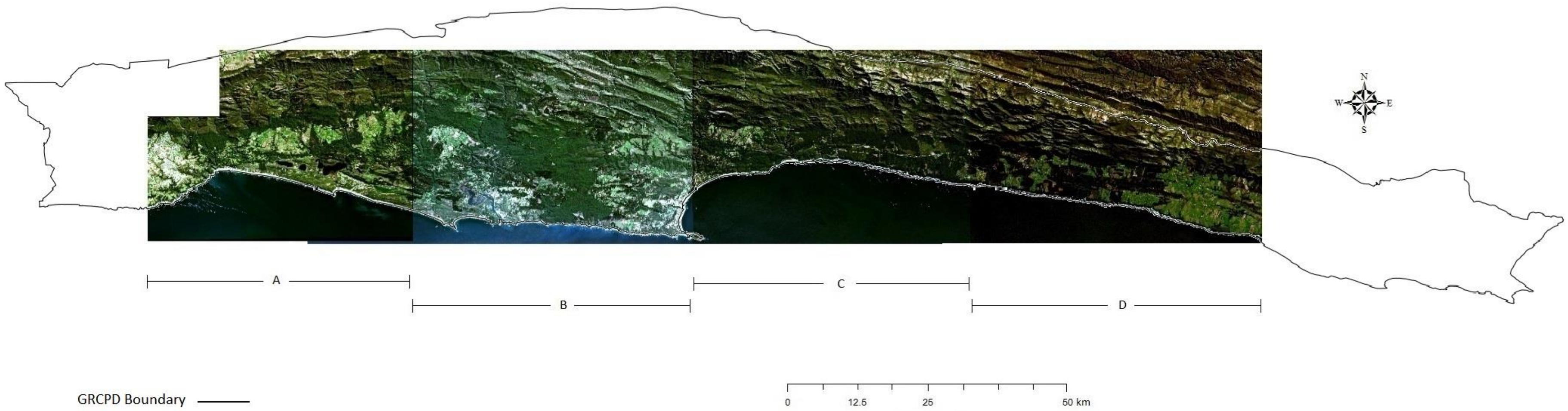

Figure 3.6. The atmospherically corrected and mosaicked SPOT-6 data of the Garden Route. The east and west of the domain were not covered as cloud-free data were not available for these areas. The four images are labelled A-D (see Table 3.1).

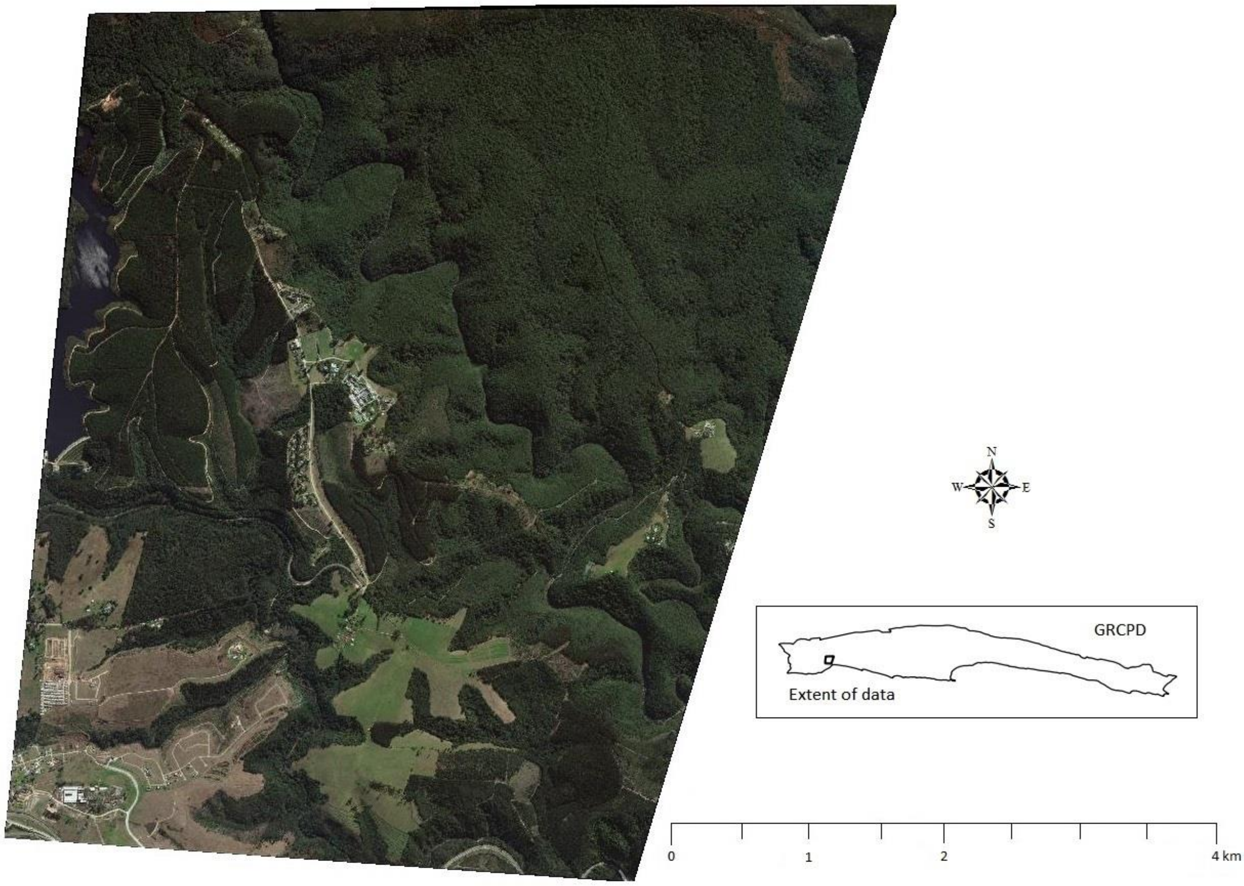

Figure 3.7. The atmospherically corrected 25 km^2 of the WV-3 data obtained from Digital Globe of a section of the study area.

The separation of vegetation species from one another benefits tremendously from using non-parametric classifiers. This is because vegetation reflectance data rarely has a normal distribution (Immitzer *et al.*, 2012). One of the most recent and successful non-parametric classifiers, Random Forest (RF) (Breiman, 2001), was successfully used in vegetation species classification with accuracies comparable to Support Vector Machines and Artificial Neural Networks classifiers (Nitze *et al.*, 2012). The RF classifier can manage small sample sizes of training data (Breiman, 2001) and can classify land cover and tree species successfully with OAs of more than 85% (Naidoo *et al.*, 2012; Rodriguez-Galiano *et al.*, 2012). This pixel-based classifier is a decision-tree algorithm, consisting of numerous trees (Breiman, 2001). It is robust against noise and typically produces high accuracy levels (Breiman, 2001). It was therefore considered the appropriate classifier for this study, particularly concerning the small size of the training data. The classifier was therefore used to separate the invasive tree species.

ROIs are areas within an image which represent a vegetation or land cover class and can guide classifications. There are two types of ROIs; training sites, which comprise the signature for each class, and test sites, which are used to assess the accuracy of the remote sensing classification (Lillesand *et al.*, 2015). Training sites are areas with reflectance values which are representative of a class, and can therefore be used to teach the classifier which cells should be included in each class. Test sites are areas which can be used to find the accuracy of the classification (Lillesand *et al.*, 2015).

The larger the training site, the greater the classification accuracy is likely to be (Foody & Mathur, 2006). However, as all training and test sites have to be the same size to be comparable, the number of pixels that can be used for one ROI is restricted by the class with the smallest area. In this study, it was the invasive tree classes. Since a typical canopy diameter was 2-3 m, an individual tree scarcely covered one SPOT-6 pixel. Therefore, a single tree would have been subject to edge and background effects, such as mixed classes and soil reflectance (Foody & Mathur, 2004, 2006). To mitigate for this, an area was only used as an invasive tree ROI if the canopy was comprised of multiple trees.

To run the SPOT-6 classifications, various vegetation and land classes were used. For the initial classification of SPOT-6 data, 40 training and 20 test sites were captured for each of the nine classes (Table 3.2). These classes were: Acacia, Agriculture, Aquatic ecosystem, Eucalypt, Fynbos, Indigenous forest, Pine, Plantation and Urban. The SPOT-6 classification of the George and Wilderness area had eight classes: Acacia, Agriculture, Aquatic ecosystem, Eucalypt, Fynbos, Indigenous forest, Pine and Urban and used single-pixel ROIs. The Plantation class was removed because many of the plantation species in the Garden Route are *Pinus*, and this had caused confusion between the Planation and Pine classes in the previous SPOT-6 classification.

For the SPOT-6 classification of the George and Wilderness area, the ROIs were one pixel wide. Smaller ROIs were used because in the previous SPOT-6 classification of the Garden Route (with ROIs representing four pixels), the invasive tree ROIs were subject to the effects of the other vegetation or land classes (see Section 5.2.1). As this meant fewer pixels being included, 100 ROIs per class were used as training sites and 50 ROIs were captured for test data for the classification of the George and Wilderness area (Table 3.2). In total across the eight land classes 800 ROIs where used for training and 400 for testing.

For the WV-3 classification, the classes were: Acacia, Agriculture, Aquatic ecosystem, Bare ground Eucalypt, Fynbos, Indigenous forest, Pine and Urban. A Bare ground class was added because such areas were more prevalent in the WV-3 extent compared to the extent of the SPOT-6 imagery.

Owing to the smaller extent of the WV-3 data, there were fewer GPS points of the focal invasive tree species available for use in capturing ROIs for the tree classes. This limited the number of ROIs captured to 25 for all classes. This was then split into 15 training sites (60%) and 10 test (40%).

The ROIs for the WV-3 classification were four (two by two) pixels (Table 3.2). This was an increase on the single-pixel ROIs used in the SPOT-6 classification of the George and Wilderness area because these ROIs had struggled to capture the reflectance variation of a class (see Section 4.2.2 and Foody & Mathur (2006)). Using ROIs of this size ensured a compromise between the number that could be captured and ROI spectral range diversity.

Table 3.2. The size and quantity of training and test sites (collectively known as ROIs) for the classifications of SPOT-6 and WV-3 data in the Garden Route.

Data	ROI size (pixels)	Area represented by one ROI (m^2)	Number of training sites	Number test sites	Number of classes
SPOT-6 Garden Route	4	24	40	20	9
SPOT-6 George and Wilderness	1	6	100	50	8
WV-3	4	4.96	15	10	9

The ROIs for the SPOT-6 and WV-3 data were captured in the ENvironment for Visualizing Images (ENVI) software (Exelis, 2015). Once all training ROIs were fed in, they were merged to create a signature file. The same process was completed for the test sites.

Classified images were created with the SPOT-6 and WV-3 data in ENVI to be exported to the Environmental Mapping and Analysis Programme Box (EnMAP-Box) software, a freely available application for image classification (Van der Linden *et al.*, 2015). Here, the RF classification was run on the SPOT-6 and WV-3 data. The resulting images showed the vegetation and land cover classes and indicated the presence of the selected focal invasive tree species in areas across the study area.

The classification accuracy was assessed by comparing classified values against known values (Lillesand *et al.*, 2015). The accuracy target for each class was a minimum of 70% (Thomlinson *et al.*, 1999). The accuracy assessments for the RF classifications of the SPOT-6 and WV-3 were performed in EnMAP-Box and reported using a confusion matrix (see Tables 4.3, 4.4 and 4.5 for results).

3.5 Formulating prioritisation criteria for the management of invasive tree species

Weighting criteria is a method of prioritising invasive tree management. A concept for managing hierarchies of criteria, known as the Analytic Hierarchy Process (AHP), was first developed by Saaty (1990). As several studies have already compiled weighted criteria for the prioritisation of IAP management (Table 3.3), these were used to derive the criteria and weightings for this study.

Several studies were found using a literature search for prioritising IAP and land management in South Africa. Studies were included if they were based in the Western Cape or focused specifically on aquatic ecosystems or fynbos. Studies prioritising IAPs in fynbos were included as this habitat is predominantly found in the Western Cape and covers a large area of the Garden Route. One national study (Van Wilgen *et al.*, 2007) was used as the results were relevant to prioritising rivers in the Garden Route. For any study which did not give weightings for their criteria, such as Van Wilgen *et al.* (2007), the criteria were all considered to have equal weight. Six studies were found to be relevant and were subsequently included in the criteria for this study (see Table 2.4).

Several of the prioritisation studies also provided sub-criteria. For this research, criteria were only divided in sub-criteria if they were applicable to conserving aquatic ecosystems and their weighting exceeded the weight of next highest criteria in their original study. For example in Forsyth *et al.* (2015), 'Special conservation areas' (a sub-criterion of 'Conservation and biodiversity importance') had a weighting of 26.34% (see Table 2.4). This was more than the value of the next-highest weighted criterion, 'Value of the land for water production,' which had a value of 25.62%, and therefore 'Special conservation areas' were included.

Certain criteria for the ranking of invasive species as priorities were excluded from analysis in this study. Criteria were only included in the SCP analysis if they were applicable to restoring aquatic ecosystems and their associated ecosystem services. Socio-economic criteria, such as reducing poverty and unemployment, can conflict with ecological considerations (McConnachie *et al.*, 2012) and do very little towards restoring aquatic ecosystems, and were therefore excluded from subsequent analysis. The criterion prioritising sites which 'Experienced the largest habitat loss' (Van Wilgen *et al.*, 2007) was also excluded. This was because no existing data were available to calculate it and, as a low-weighted criterion, its impact on the SCP results would have been minimal and therefore not cost-effective to measure. Criteria which are a consideration for management, such as the presence of existing management or accessibility, were grouped together.

Table 3.3. The suitability of available spatial data for prioritising invasive tree management in the Garden Route.

Criteria	Studies which included it	Spatial data available	Date captured	Scale digitised at	Source	Possible issues with data use
Value of the land for water	Van Wilgen *et al.* (2007, 2008a), Forsyth *et al.* (2009, 2012, 2015), Forsyth & Le Maitre (2011)	National Wetland Map 5	2009 - 2016	1:500-1:2000	Van Deventer (2016a)	None identified at this stage
		Strategic Water Source Areas (SWSAs)	July 2013	1 x 1 minute grid cell resolution	SANBI (2013)	None identified at this stage
Presence of priority IAPs	Van Wilgen *et al.* (2007, 2008a), Forsyth *et al.* (2009, 2012), Forsyth & Le Maitre (2011)	-	-	-	-	To be assessed during this study
High potential invasion areas	Van Wilgen *et al.* (2007), Forsyth & Le Maitre (2011), Forsyth *et al.* (2015)	Plantation boundaries	2008-2009	1:5 000 - 1:10 000	SANBI (2010a)	These data have been archived by SANBI
		Rivers	July 2011	1:500 000	SANBI (2011)	None identified at this stage
		Roads	Variable	Variable	Open Street Map (2016)	
			2009	Variable	SANParks	
Value of the land for biodiversity/ Critical Biodiversity Areas (CBAs)*	Van Wilgen *et al.* (2008a), Forsyth *et al.* (2009, 2012, 2015), Forsyth & Le Maitre (2011)	CBAs Ecological Support Areas (ESAs)	2008-2009	1:5 000 - 1:10 000	(SANBI, 2010d)	These data have been archived by SANBI
Existing management in place/ Accessible areas	Forsyth *et al.* (2009, 2012), Forsyth & Le Maitre (2011)	Protected areas	2008-2009	1:5 000 - 1:10 000	(SANBI, 2010d)	These data have been archived by SANBI
		Digital Elevation Model (DEM)	2015	30 m resolution	United States Geological Survey (2015)	
Presence of endangered species	Forsyth *et al.* (2015)	CBAs	2008-2009	1:5 000 - 1:10 000	(SANBI, 2010d)	The presence of endangered species is just one of three considerations for CBAs (Holness *et al.*, 2010)

* The criterion 'Value of the land for biodiversity' was used synonymously with CBAs (see Section 2.4 for definition)

The average weighting of each review-based criterion across the six published studies (Table 2.4) was calculated. These averages were then totalled and each criterion's weighting was divided by this amount.

For example, the total of the value of the land for water criterion was 135.32 (25.62 + 22.30 + 4.60 + 12.10 + 45.70 + 25.00) across the six studies, an average of 22.55. This average was then divided by the sum of all the criteria weights (79.89) to give a weighting of 28.23% for the value of the land for water criterion in this study. This provided the weightings for each criterion in this study (see Table 4.7).

3.6 Prioritising areas for invasive tree management using spatial data

As areas important for water-dependent ecosystem services were deemed the highest priority for management (see Section 2.2), they had to be identified. This included sites such as aquatic ecosystems and Strategic Water Source Areas (SWSAs). SWSAs are important for providing a supply of clean, fresh water, which helps to ensure aquatic ecosystem functioning (Nel *et al.*, 2013). Aquatic systems and SWSAs were both given equal weighting in the prioritisation process for representing land valuable for water.

To identify areas for invasive tree colonisation, the criteria 'High potential invasion areas' and 'Presence of priority IAPs' were combined to create the criterion 'Invasion of IAPs.' This was used as a disturbance index, indicating areas most prone to IAP invasion. Disturbed areas are susceptible to invasion and are important for invasive tree management (Forsyth *et al.*, 2015). They were defined as: plantation boundaries, rivers, roadsides and main footpaths (Parendes & Jones, 2000; Alston & Richardson, 2006; McConnachie *et al.*, 2012; Baard & Kraaij, 2014; McConnachie *et al.*, 2015).

For road data, two sources were used. Data from the GRNP were obtained from SANParks and data for the remaining sections of the Garden Route were obtained from Open Street Map (Open Street Map, 2016). The main roads of the Open Street Map data (labelled as motorways, primary, secondary, tertiary and trunk) and paths were kept, whilst all other roads were deleted due to them being in residential areas. These two datasets were then merged.

As twice as many invasive trees are found within 3 km of plantations in the Cape Floristic Region (McConnachie *et al.*, 2015), the intention was for these areas to be deemed a higher priority than other areas. However, a 3 km buffer around plantations in the Garden Route covered approximately 4,025 km^2 of the 6,100 km^2 study area. Including this area as an input raster for the SCP analysis would have dominated the results and narrower buffer areas were therefore considered.

Since invasive species are defined as those which spread 100 m or more in less than 50 years (Richardson *et al.*, 2000; Richardson & Rejmanek, 2004), the disturbed habitats (rivers, roads, main footpaths and plantation boundaries) were buffered by 100 m along each edge to indicate priority areas for IAP management. The total area of the Garden Route within 100 m of a disturbed habitat was 1,286.54 km^2

(approximately 21% of the study area). This was more reasonable than the originally planned 3 km buffer, which covered almost two thirds of the study area. The plantations themselves were erased from the newly created layer because they are managed separately from natural areas. As transformed areas were to be excluded (see Section 2.7.3), roads and urban areas were also removed.

For the finalised disturbed areas shapefile, all the GPS points of the focal trees (see Section 3.2.2) were incorporated as these were within 100 m of a road. The classification results which classified the invasive tree classes with 70% OA or more (see Table 4.5) were also included. A map showing the disturbed areas within the Garden Route is presented in Appendix 5.

Vital considerations for land management in South Africa are Critical Biodiversity Areas (CBAs) and Ecological Support Areas (ESAs) (Driver *et al.*, 2012). ESAs are sites which support CBAs and protected areas and which should be preserved in a functioning state to safeguard biodiversity (Vromans *et al.*, 2010; Driver *et al.*, 2012). Both CBAs and ESAs help to maintain biodiversity and ecosystem services (Vromans *et al.*, 2010) (see Table 3.3). In this study, ESA took the weightings for the criterion 'Value of the land for biodiversity/CBAs' and CBAs were used to represent the criteria 'Value of the land for biodiversity/CBAs' and 'Presence of endangered species.' This was because the presence of endangered species is used to identify CBAs (Holness *et al.*, 2010). This pragmatic approach also ensured that CBAs, which carry more conservation importance, had a higher weighting in this study than ESAs.

For IAPs to be effectively managed, the land must be accessible (SANParks, 2010). A 30 m Digital Elevation Model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) (U.S. Geological Survey, 2015) and used to locate accessible areas. Accessibility was defined as areas accessible by foot, without requiring specialised teams or equipment. One of the predominant IAP clearing organisations, Working for Water, does not clear by foot on slopes steeper than 22.5^{o} (Mudau, 2016). Therefore, slopes less than this were defined as accessible and subsequently deemed a higher priority than other areas (Figure 3.8).

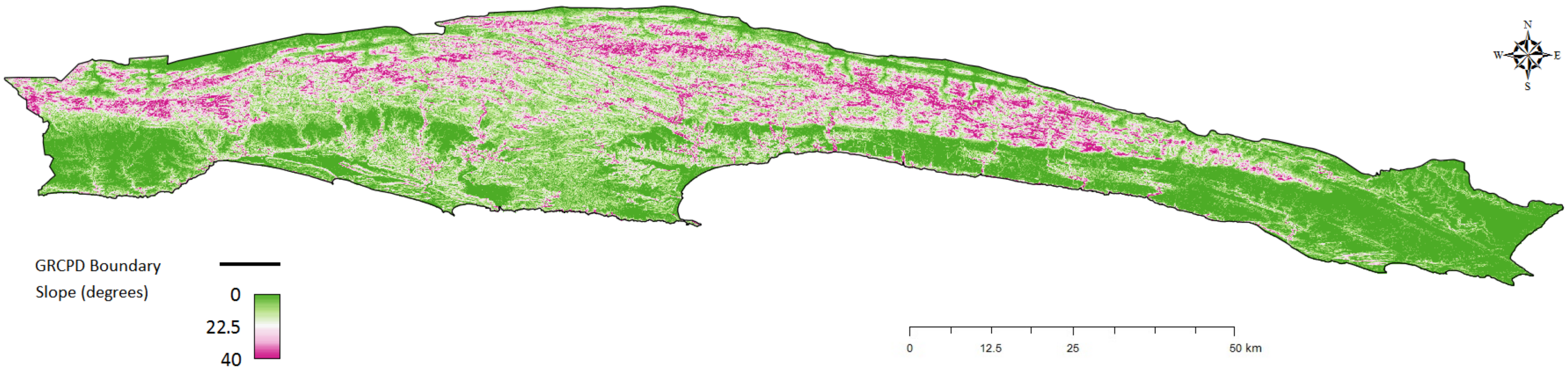

Figure 3.8. Degrees of slope as a proxy for accessibility in the Garden Route. A slope of < 22.5° was defined as accessible for invasive tree management.

Focusing on sites which have existing management in place increases the effectiveness of IAP management (Forsyth *et al.*, 2009). Therefore, existing protected areas were prioritised over non-protected ones. Shapefiles of protected areas in the Garden Route were provided by SANParks, including land managed by SANParks, CapeNature and Natural Heritage Sites. These data were later used in the SCP.

3.7 The use of spatial conservation planning software for management prioritisation

Having identified areas most susceptible to invasive tree species and developed a list of criteria to be applied to the Garden Route (see Sections 3.1 and 3.5), prioritisation for invasive tree management was performed across the study area. This was achieved with the SCP software, Zonation (University of Helsinki, 2013). Zonation has been used successfully to prioritise landscapes (Thieme *et al.*, 2007; Leathwick *et al.*, 2008; Moilanen *et al.*, 2008; Rayfield *et al.*, 2009). It was chosen over traditionally used AHP software because it produces a priority ranking through the landscape, instead of a target-based solution (Lehtomäki & Moilanen, 2013) and the input data do not have to be normalised (Lehtomäki *et al.*, 2016). This means it is more time efficient than AHP approaches (Lehtomäki & Moilanen, 2013). Zonation is able to perform data rich analysis over a large area (Lehtomäki *et al.*, 2016) and is a freely available method for conservation planning (Moilanen *et al.*, 2014).

There are several advantages to using Zonation for SCP. Zonation prioritises by removing the least valuable cells from the site, then repeating the process in the remaining area until the desired value is reached. This results in the smallest loss of biodiversity across the landscape (Lehtomäki & Moilanen, 2013). Spatial data and previously published prioritisation results can be incorporated into the software. Zonation also links the connectivity of the area with any user defined objectives or weightings to provide an optimal management strategy (Lehtomäki & Moilanen, 2013). Features than can be prioritised include species (Moilanen *et al.*, 2005) and ecosystems (Lehtomäki & Moilanen, 2013). Considerations such as irreplaceability, replacement cost and the effectiveness of the area at conserving biodiversity can also be included (Kukkala & Moilanen, 2013). It can analyse landscapes which consist of tens of millions of grid cells (Arponen *et al.*, 2012). Zonation was therefore considered appropriate for prioritisation in the Garden Route.

3.8 The Method of integration into Zonation

To prepare the spatial data for input into Zonation, rasterisation had to take place. Each of the shapefiles representing the prioritisation criteria (shown in Table 3.3) were converted from vector to raster format in ArcMap based on the acquired 30 m DEM raster. This ensured all input data had identical resolutions. Urban areas and plantations were excluded as they are transformed habitats and are therefore not a management priority. Using the weightings of criteria identified by relevant IAP prioritisation studies in South Africa (Table 3.4), the rasters were put into Zonation.

For the SCP analysis, the additive benefit cell removal model was selected. It was chosen over the Core-area Zonation function because it removes the cells with the smallest sum value of weightings as opposed to the cells with the lowest maximum weighting (Moilanen *et al.*, 2014). This meant all criteria weightings in each cell were considered, rather than just the highest weighted criteria in each cell. The results of the analysis showed which areas of the Garden Route should be prioritised for invasive tree control and can be seen in Figure 4.7.

Table 3.4. The review-based data input into the SCP software, Zonation, to prioritise invasive tree management across the Garden Route. For a full description of the data and how it was used in this study, see Table 3.3. See Appendices 3-10 for maps of the input spatial data.

Data	Review-based criteria represented	Weighting /100
Aquatic ecosystems	Value of the land for water	28.23
SWSAs	Value of the land for water	28.23
Disturbed areas	Invasion of IAPs	24.43
CBAs	Value of the land for biodiversity/CBAs + Presence of endangered species	(21.35 + 6.15) = 27.50
ESAs	Value of the land for biodiversity/CBAs	21.35
Protected areas	Existing management in place	19.84
DEM	Accessible areas	19.84
Urban areas and plantations	None - this layer represents areas to mask	0.00

In the next chapter the results of the prioritisation and remote sensing analyses are presented.

Chapter 4 Results

This chapter contains the results of prioritising invasive tree species for their control, thus helping to conserve aquatic ecosystems in the Garden Route. The results address the objectives of this study, which were: to spatially locate invasive tree species in the Garden Route, to formulate prioritisation criteria for the management of invasive tree species and to apply these prioritisation criteria to identify priority areas for invasive tree species management (see Section 1.7).

4.1 The invasive tree species which are a management priority in the Garden Route

To identify priority invaders in the Garden Route, literature on the impacts of Invasive Alien Plants (IAPs) was analysed. Seven studies were chosen which provided lists of priority species. As introduced in Chapter 2, an IAP had to meet certain criteria (Table 4.1) to be included as a priority species. It had to a) be a tree (Van Wilgen *et al.*, 2008a), b) be a transformer (Baard & Kraaij, 2014) and c) negatively impact aquatic ecosystems (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008b; Forsyth *et al.*, 2012) (see Section 2.7.2 for a definition of a transformer species and Figure 3.1 for the decision tree showing the steps in identifying priority species).

Table 4.1. Criteria for determining priority invasive tree species for management of aquatic ecosystems in the Garden Route.

Criteria	Decision rule	Reference	Rationale for use in this study
Tree species must be a transformer	Does the species have the potential to irreversibly change the structure, composition and function of a biotic community?	Baard & Kraaij (2014)	Transformer species are plants that have adverse environmental impacts and should be a management priority (Gaertner *et al.*, 2014)
Priority tree species for riparian zones	Does species invade riparian zones?	Forsyth *et al.* (2012)	Riparian zones provide essential ecosystem services (Barling & Moore, 1994) and are vulnerable to invasive species (Zedler & Kercher, 2004)
Priority species for the Garden Route National Park (GRNP)	Has species been found to invade the GRNP?	Forsyth & Le Maitre (2011)	The GRNP is central within the study zone
Priority species for fynbos	Does species have the potential to occupy > 20% of the fynbos biome?	Van Wilgen *et al.* (2008a)	Fynbos is endemic to the Garden Route (the study area)
Affects fynbos and surface water	Does species reduce water supply to riparian zones in the fynbos biome?	Van Wilgen *et al.* (2008b)	Fynbos is endemic to the Garden Route (the study area), South Africa is a water scarce country (Ashton, 2002) and the functioning of aquatic ecosystems, and the services they provide, is dependent on water supply (Zedler & Kercher, 2005)
Priority species for rivers (riparian zones)	Does species invade riparian zones?	Van Wilgen *et al.* (2007)	Riparian zones provide essential ecosystem services (Millennium Ecosystem Assessment, 2005a) and are vulnerable to invasive species (Zedler & Kercher, 2004)
NEMBA Category 1b	Is species prohibited in the Western and/or Eastern Cape Provinces?	Government Gazette (2014)	These species are a priority for control in South Africa (Government Gazette, 2014b)

Among the seven studies in Table 4.1, 25 invasive tree species from ten genera were highlighted as problematic in the Garden Route and having detrimental effects on aquatic ecosystems (Table 4.2). Of these species, the following six only met one of the seven criteria (in Table 4.1). These were: *Acacia baileyana*, *A. decurrens, Jacaranda mimosifolia*, *Pinus patula*, *Populus alba*, *Prosopis glandulosa* and *Salix babylonica*. Four species met two of the criteria: *Acacia elata Eucalyptus diversicolor, Melia azedarach* and *Pinus halepensis*. Three species met three criteria: *Acacia pycnantha, Eucalyptus cladocalyx, E. lehmannii*. Two species, *Acacia melanoxylon* and *Leptospermum laevigatum,* met the minimum number of criteria (four), however only *A. melanoxylon* is a transformer species. *A. cyclops*, *Pinus pinaster, P. radiata, Populus x. canescens* and *Paraserianthes lophantha* each met five of the seven criteria, although *Populus x. canescens* and *Paraserianthes lophantha* were not transformer species. No species met all seven criteria but *Eucalyptus camaldulensis, Acacia longifolia, A. mearnsii* and *A. saligna* each met six.

After applying the requirements for inclusion in this study, eight of the 25 tree species were found to be a priority for management in the Garden Route (Table 4.2). All eight are a threat to aquatic ecosystems in the Garden Route as they reduce water availability to riparian zones (Van Wilgen *et al.*, 2008b). These species were: *Acacia cyclops*, *A. longifolia*, *A. mearnsii*, *A. melanoxylon*, *A. saligna*, *Eucalyptus camaldulensis*, *Pinus pinaster* and *P. radiata*. Each of the eight focal species is a priority species for the GRNP (Forsyth & Le Maitre, 2011) and uses excessive water (Van Wilgen *et al.*, 2008b). *Eucalyptus camaldulensis* was included, despite not being a transformer, because it met the six other criteria, including being a Category 1b invasive (Government Gazette, 2014b).

Table 4.2. The criteria for identifying priority invasive tree species for the Garden Route. Species highlighted in grey were included in the subsequent remote classifications. A transformer is an IAP which changes ecosystem conditions over a considerable proportion of an ecosystem (Richardson *et al.*, 2000). A priority tree species for the Garden Route is a transformer which meets at least three other criteria, including negatively impacting surface water or riparian zones (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008b; Forsyth *et al.*, 2012) (see Figure 3.1 for the decision tree used to identify priority species).

Species	Criteria							Invades aquatic ecosystems
	Transformer (Baard & Kraaij, 2014)	Priority tree species for riparian zones (Forsyth *et al.*, 2012)	Priority species for rivers (Van Wilgen *et al.*, 2007)	Affects fynbos and surface water (Van Wilgen *et al.*, 2008b)	Priority species for the GRNP (Forsyth & Le Maitre, 2011)	Priority species for fynbos (Van Wilgen *et al.*, 2008a)	NEMBA Category 1b* (Government Gazette, 2014b)	
Acacia longifolia (long-leaved wattle)	X	X		X	X	X	X	X
Acacia mearnsii (black wattle)	X	X	X	X	X	X		X
Acacia saligna (Port Jackson willow)	X	X		X	X	X	X	X
Eucalyptus camaldulensis (red river gum)		X	X	X	X	X	X	X
Acacia cyclops (rooikrans)	X			X	X	X	X	X
Paraserianthes lophantha (stink bean)		X		X	X	X	X	X
Pinus pinaster (cluster pine)	X		X	X	X		X	X
Pinus radiata (radiata pine)	X		X	X	X		X	X
Populus x. canescens (grey poplar)		X	X	X	X	X		X
Acacia melanoxylon (blackwood)	X			X	X	X		X
Leptospermum laevigatum (Australian myrtle)				X	X	X	X	
Acacia pycnantha (golden wattle)		X			X	X		X
Eucalyptus cladocalyx (sugar gum)					X	X	X	

Eucalyptus lehmannii (bushy yate)				X	X	X		
Acacia elata (cedar wattle)					X		X	
Eucalyptus diversicolor (Karri gum*)*					X		X	
Melia azedarach (Persian lilac)				X			X	X
*Pinus halepensis (*Aleppo pine)				X		X		
Acacia baileyana (Bailey's wattle)				X				X
Acacia decurrens (green wattle)	X							
Jacaranda mimosifolia (blue jacaranda)	X							
Pinus patula (patula pine)			X					X
Populus alba (white poplar)		X						X
Prosopis glandulosa (mesquite)			X					X
Salix babylonica (weeping willow)			X					X

* National Environmental Management Biodiversity Act (NEMBA) (Act No. 10 of 2004) species are only shown if they are included by one of the six other studies

4.2 Results of spatially detecting priority invasive tree species in the Garden Route on SPOT-6 data

In this section, the results of the RF classifications of *Satellite Pour l'Observation de la Terre-6* (SPOT-6) data are reported (Figures 4.1 and 4.2 and Tables 4.3 and 4.4). The Overall Accuracy (OA), Producer's Accuracy (PA) and User's Accuracy (UA) are given for both the SPOT-6 classification of the Garden Route (Section 4.2.1) and the George and Wilderness area (Section 4.2.2). OA is the total number of correctly classified pixels as percentage of the total number of pixels classified (Woodcock *et al.*, 2002). PA is the number of correctly classified pixels divided by the total number of pixels that should have been in that class (i.e. the column total) and UA is the number of correctly classified test pixels divided by the total number of pixels in that class (i.e. the row total) (Woodcock *et al.*, 2002). Kappa indices are not shown as they are misleading and their use is limited (Pontius *et al.*, 2011).

4.2.1 The SPOT-6 classification of the Garden Route

The majority of the tree species were poorly separated in the SPOT-6 classification of the Garden Route. Table 4.3 shows the confusion matrix (a table showing the performance of the classification by checking against the test sites) of the results in which the OA, PA and UA are reported for each class. For the Acacia, Eucalypt and Pine classes, only 7.5, 37.5 and 47.5% of the test ROIs were correctly classified (PA). These values were all below the target accuracy of 70% (Thomlinson *et al.*, 1999).

There were large amounts of spectral confusion between the tree classes. Of the Acacia test ROIs, 23.8% were classified as Eucalypt, a further 23.8% were classified as Pine and 20% were classified as Indigenous forest. For the Eucalypt class, the highest amounts of confusion were with the Pine and Plantation classes (11.3 and 13.8% respectively). The majority of confusion with the Pine test sites occurred between the Plantation (18.8%) and Indigenous forest classes (11.3%). These errors were likely caused by the four bands of SPOT-6 limits the ability to separate between these classes.

The SPOT-6 data consisted of four images merged together (labelled A-D) and these images were inconsistently classified owing to variation in illumination and atmospheric conditions across the four dates of the images. For example, an area might have been classed as a plantation in Image C but as indigenous forest on the neighbouring Image D. In the south of Image B, around Knysna and Plettenberg Bay (Figure 4.1), areas were misclassified as Acacia but this misclassification was not present in other areas or images. The large number of errors in the classification indicates that the SPOT-6 classification of the Garden Route was not successful at separating invasive tree species.

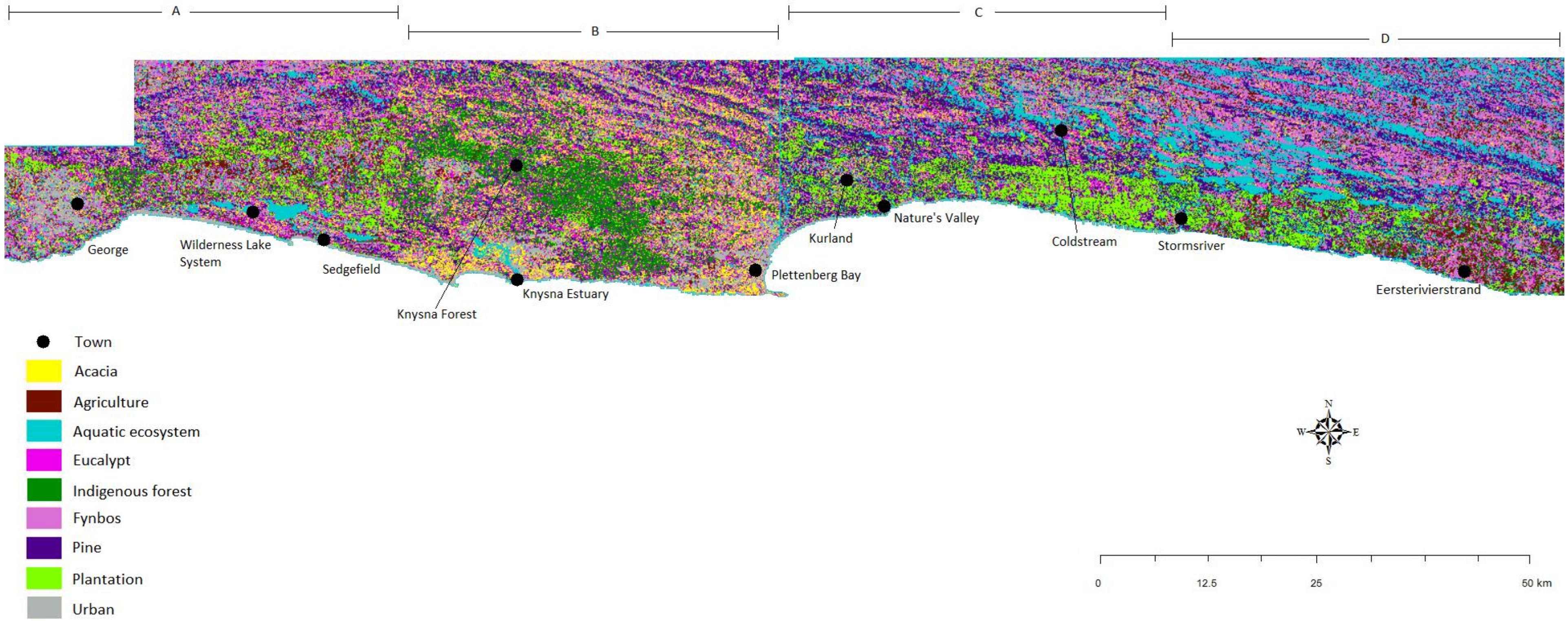

Figure 4.1. Results of the SPOT-6 classification of the Garden Route indicating the location of invasive *Acacia, Eucalyptus* and *Pinus* species and other land classes. The four SPOT-6 images are labelled A-D.

Table 4.3. Confusion matrix for the SPOT-6 classification of the Garden Route, showing the percentage of correctly classified pixels for each class in the diagonal grey cells. The Overall Accuracy (OA) is calculated as the average of the correctly classified pixels and given as a percentage. UA is the number of correctly classified test pixels divided by the total number of pixels in that class given as a percentage (i.e. the row total) and PA is the number of correctly classified pixels divided by the total number of pixels that should have been in that class given as a percentage (i.e. the column total) (Woodcock *et al.*, 2002). Row elements represent the percentage of ROIs from each class which were classified in each class and the columns show where the test ROIs for each class were placed by the classification.

Class	**Acacia**	**Agriculture**	**Aquatic ecosystem**	**Eucalypt**	**Fynbos**	**Indigenous forest**	**Pine**	**Plantation**	**Urban**	**SUM**	**UA (%)**
Acacia	7.50	6.25	2.50	8.75	2.50	0.00	3.75	0.00	10.00	41.25	18.18
Agriculture	1.25	35.00	1.25	6.25	8.75	0.00	0.00	0.00	5.00	57.50	60.87
Aquatic ecosystem	0.00	5.00	72.50	0.00	10.00	10.00	5.00	0.00	6.25	108.75	66.67
Eucalypt	23.75	17.50	1.25	37.50	10.00	8.75	10.00	10.00	8.75	127.50	29.41
Fynbos	10.00	18.75	11.25	7.50	62.50	1.25	3.75	1.25	10.00	126.25	49.50
Indigenous forest	20.00	1.25	0.00	10.00	0.00	25.00	11.25	7.50	0.00	75.00	33.33
Pine	23.75	3.75	11.25	11.25	1.25	28.75	47.50	17.50	3.75	148.75	31.93
Plantation	7.50	1.25	0.00	13.75	0.00	26.25	18.75	63.75	0.00	131.25	48.57
Urban	6.25	11.25	0.00	5.00	5.00	0.00	0.00	0.00	56.25	83.75	67.16
SUM	100	100	100	100	100	100	100	100	100	900	
PA (%)	7.50	35.00	72.50	37.50	62.50	25.00	47.50	63.75	56.25		**OA = 40.75%**

4.2.2 The SPOT-6 classification of George and Wilderness

The SPOT-6 classification of the George and Wilderness area achieved a higher OA than the SPOT-6 classification of the Garden Route (62.5% compared to 40.8%) (Figure 4.2 and Table 4.4). However, this was still below the 70% target. The PAs for the Acacia, Eucalypt and Pine classes were 72, 30 and 48% respectively. This meant the Acacia class was the only one of the three invasive tree classes to show a substantial improvement by 64.5 percentile points on the SPOT-6 classification of the Garden Route (see Table 4.6 for a comparison of the classifications), which appears to be an anomalous result. The SPOT-6 classification of the George and Wilderness area (OA=63%) was better classified than that of the Garden Route (OA=41%). This indicates that increasing the quantity of the ROIs but reducing the size, generally speaking, improved the accuracy of the SPOT-6 classification.

Similarly to the SPOT-6 classification of the Garden Route, spectral confusion between the tree classes was high for the classification of the George and Wilderness area. Of the test sites for the Eucalypt class, 26% were classified as Pine and 16% as Acacia. For the Pine class, the highest confusion was with the Eucalypts (26% wrongly classified as Eucalypts). The Acacia class was mostly confused with the Indigenous forest class (20% incorrectly classified as Indigenous forest). Yet of the three invasive tree classes, Acacia was the most separable, as demonstrated by the PAs for the tree classes. This could be due to Acacia class being the most spectrally dissimilar within the four bands of the SPOT-6 imagery compared to the other tree classes as well as due to the canopy size of the trees.

The UA for the Acacia class was low (62%) as large numbers of the other tree classes' test ROIs were classified as Acacia (16 for Eucalypt and 18% for Indigenous forest) (Table 4.4). The results showed large areas of Acacia which do not accurately depict the distribution of these trees (Figure 4.2). Therefore, due to the low confidence in the species' distribution, the results of the classification are of minimal use in invasive tree management. Owing to the low accuracies achieved by the classification, it can be concluded that SPOT-6 is ineffective at separating invasive *Acacia, Eucalypt* and *Pinus* trees in the Garden Route.

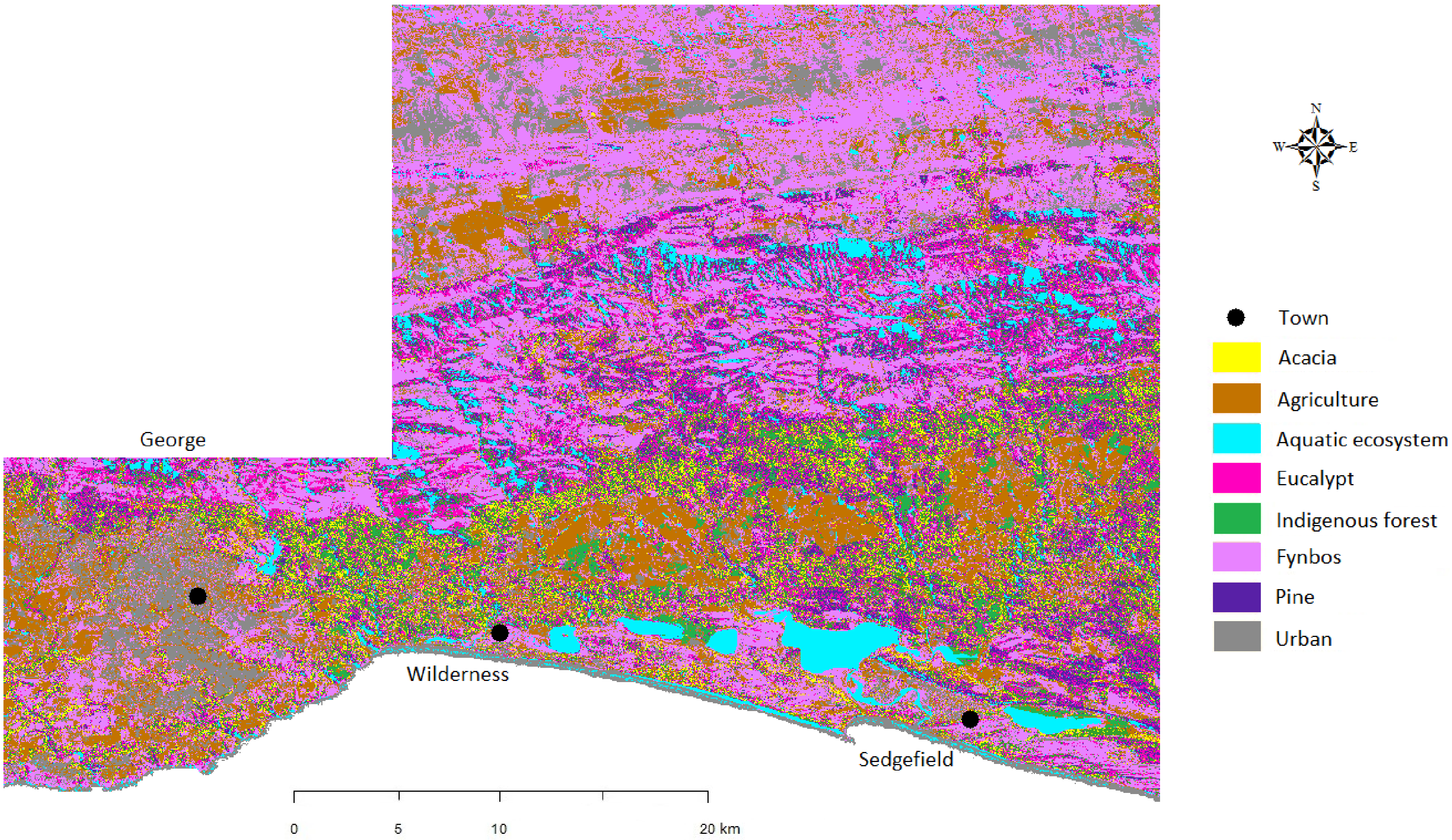

Figure 4.2. Results of the SPOT-6 classification of the George and Wilderness area indicating the location of invasive *Acacia, Eucalyptus* and *Pinus* species and other vegetation or land cover classes.

Table 4.4. Confusion matrix for the SPOT-6 classification of the George and Wilderness area, showing the percentage of correctly classified pixels for each class in the diagonal grey cells. The Overall Accuracy (OA) is calculated as the average of the correctly classified pixels and given as a percentage. UA is the number of correctly classified test pixels divided by the total number of pixels in that class given as a percentage (i.e. the row total) and PA is the number of correctly classified pixels divided by the total number of pixels that should have been in that class given as a percentage (i.e. the column total) (Woodcock *et al.*, 2002). Row elements represent the percentage of ROIs from each class which were classified in each class and the columns show where the test ROIs for each class were placed by the classification.

Class	Acacia	Agriculture	Aquatic ecosystem	Eucalypt	Fynbos	Indigenous forest	Pine	Urban	SUM	UA (%)
Acacia	72.00	0.00	2.00	16.00	2.00	18.00	6.00	0.00	116	62.07
Agriculture	6.00	54.00	4.00	6.00	16.00	8.00	4.00	4.00	102	52.94
Aquatic ecosystem	0.00	0.00	92.00	2.00	0.00	0.00	2.00	0.00	96	95.83
Eucalypt	2.00	0.00	0.00	30.00	6.00	12.00	26.00	0.00	76	39.47
Fynbos	0.00	30.00	0.00	2.00	68.00	0.00	2.00	4.00	106	64.15
Indigenous forest	20.00	2.00	2.00	18.00	0.00	44.00	8.00	0.00	94	46.81
Pine	0.00	0.00	0.00	26.00	0.00	18.00	48.00	0.00	92	52.17
Urban	0.00	14.00	0.00	0.00	8.00	0.00	4.00	92.00	118	77.97
SUM	100	100	100	100	100	100	100	100	800	
PA (%)	72.00	54.00	92.00	30.00	68.00	44.00	48.00	92.00		**OA = 62.50%**

4.3 Results of spatially locating priority invasive tree species in the Garden Route using the Random Forest classifier on WorldView-3 data

The classification results using the WorldView-3 (WV-3) imagery are shown in Figure 4.3 and Table 4.5. OA of the WV-3 classification was 78.9%, almost double that of the SPOT-6 classification of the Garden Route (40.8%). A comparison of the overall, producer and user accuracies of the WV-3 and SPOT-6 data can be found in Table 4.6. As the OA of the WV-3 classification was above the universally accepted threshold accuracy of 70% (Thomlinson *et al.*, 1999), these results demonstrate that WV-3 data are able to detect invasive *Acacia, Eucalyptus* and *Pinus* species in the Garden Route.

The PAs and UAs of the WV-3 classification for the invasive tree classes exceeded, or came close to, the target of 70%. The UAs for the Acacia, Eucalypt and Pine classes were 89.3, 63.1 and 76.3% respectively. The PAs were 62.5, 72.5 and 72.5%. This means that the PAs of the Acacia, Eucalypt and Pine classes from the eight-band WV-3 classification improved by >40 percentile points, compared to the four-band SPOT-6 classification of the Garden Route. The PA for the Acacia class for the WV-3 classification was, however, 20 percentile points less than that of the SPOT-6 classification of the George and Wilderness area (see Table 4.6 for a comparison of the classifications). Nevertheless, the addition of the red edge and yellow bands of the WV-3 data improved the separability of the SPOT-6 classifications for the invasive tree classes.

The WV-3 classification indicated areas which have large amounts of invasion by the focal species (Figure 4.3). The classification identified clusters of *Pinus* trees proximal to the plantations and it is possible that the trees could have escaped from these areas. *Acacia* trees and further *Pinus* trees were detected adjacent to the Indigenous forests, which are typically disturbed habitats (Geldenhuys *et al.*, 1986). *Eucalyptus* trees were detected across the extent of the image but higher densities were found near the rivers. Although these initial findings should be verified in the field, they indicate the importance of disturbed areas for invasive tree management.

WV-3 consistently provided better classification results than both the SPOT-6 classifications. Figure 4.4 shows the result of the SPOT-6 classification of the George and Wilderness area within the same extent of the classified WV-3 data. Based on knowledge of the area, the distribution of invasive trees classified by the WV-3 is likely more representative of the tree's distribution. For example, the Indigenous forest class was better classified by the WV-3 classification compared to the SPOT-6 classification in the same extent. The SPOT-6 classification showed expanses of *Acacia* and *Eucalyptus* invasion within the Indigenous forest, as a result of the influence of shadows in these areas. As the SPOT-6 classification of the George and

Wilderness area achieved low accuracies (mostly <63% PA and UA), it can be assumed that the classification of invasive trees in this area is largely incorrect.

The invasive tree classes for the WV-3 and SPOT-6 classification of the George and Wilderness area are shown in Figures 4.5 and 4.6. The WV-3 classification was able to identify the *Pinus* species in the plantation areas with reasonable success (PA=73; UA=76%), excluding the small sections of *Eucalyptus* it incorrectly identified in these areas. However, the SPOT-6 classification of the George and Wilderness area identified these *Pinus* plantations predominately as Indigenous forest or Acacia (Figure 4.5).

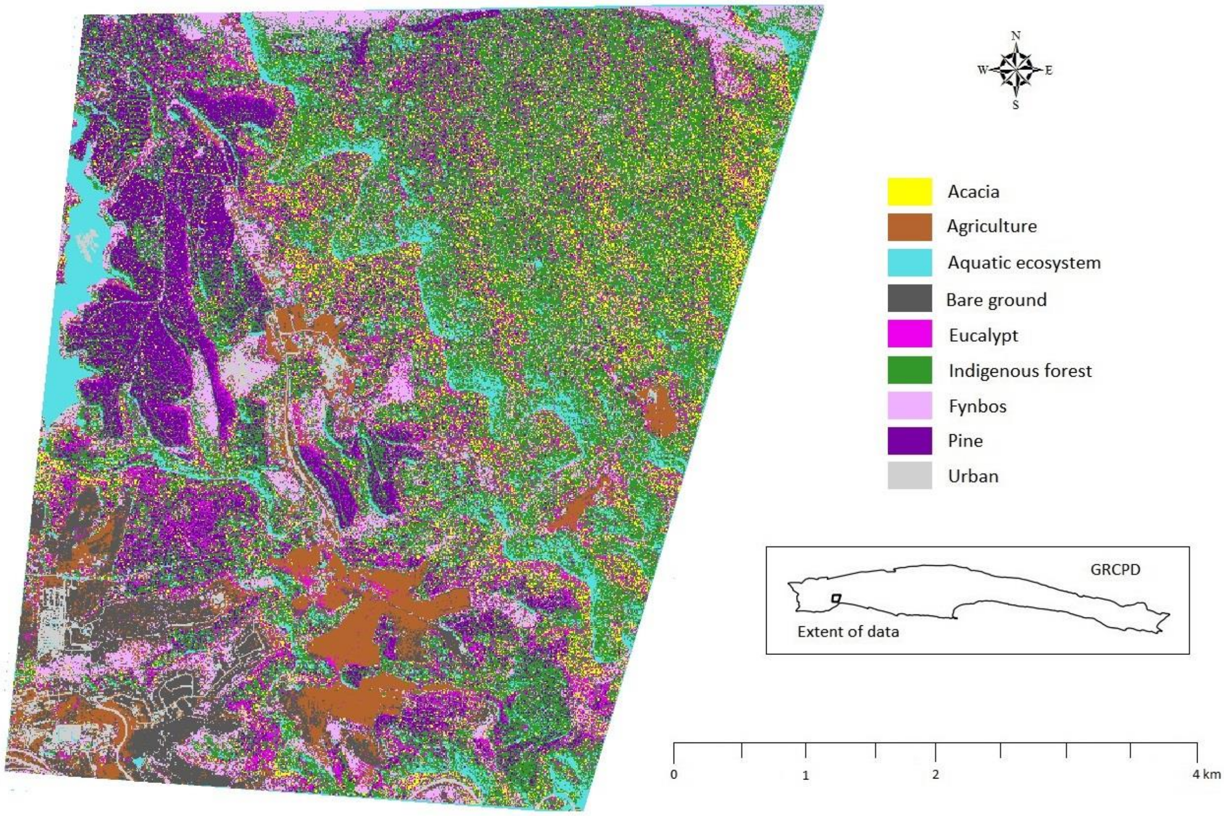

Figure 4.3. Results of the classification of WV-3 data indicating land classes and the location of invasive *Acacia, Eucalyptus* and *Pinus* species in a 25 km^2 area in the Garden Route.

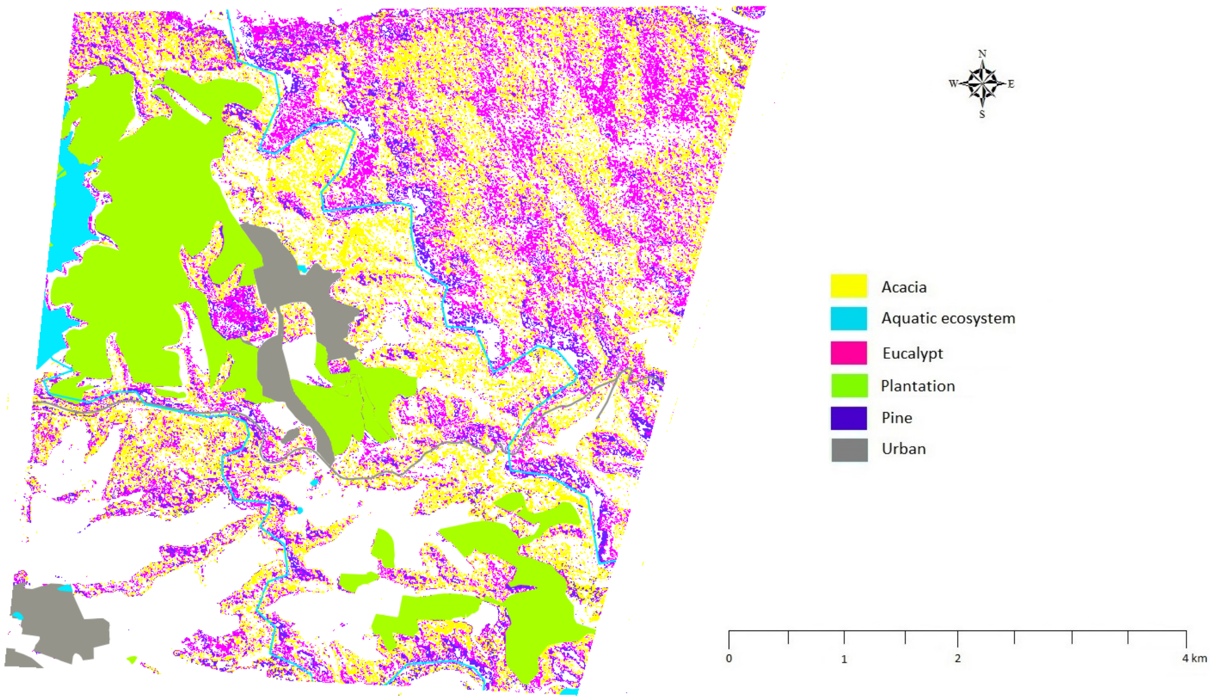

Figure 4.4. The SPOT-6 classification of the George and Wilderness area, indicating land classes and the location of invasive *Acacia, Eucalyptus* and *Pinus* species within the extent of the WV-3 data shown in Figure 4.3 (representing 25 km^2). The classes used for the two classifications differed in that the WV-3 classification included a Bare ground class.

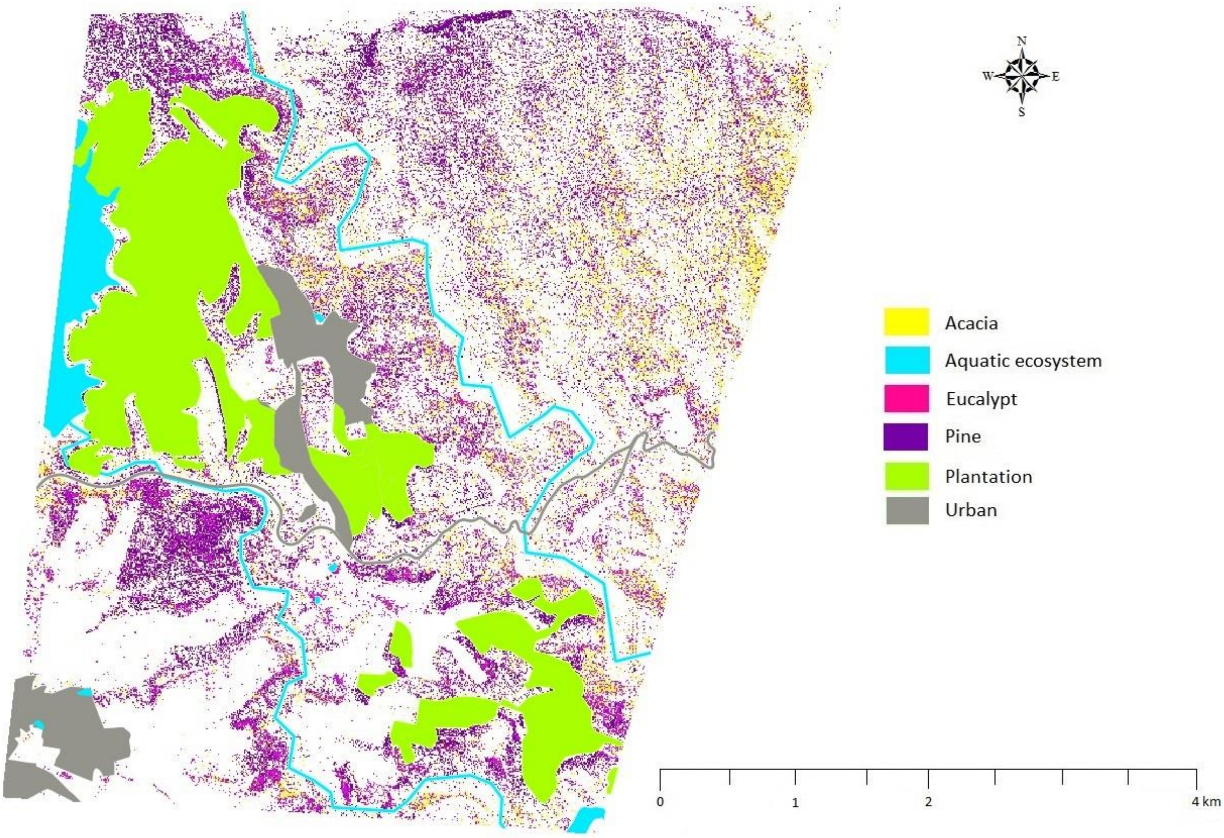

Figure 4.5. Invasive Acacia, Eucalyptus and Pinus trees detected by the WV-3 classification in relation to urban areas, plantations, aquatic ecosystems and roads.

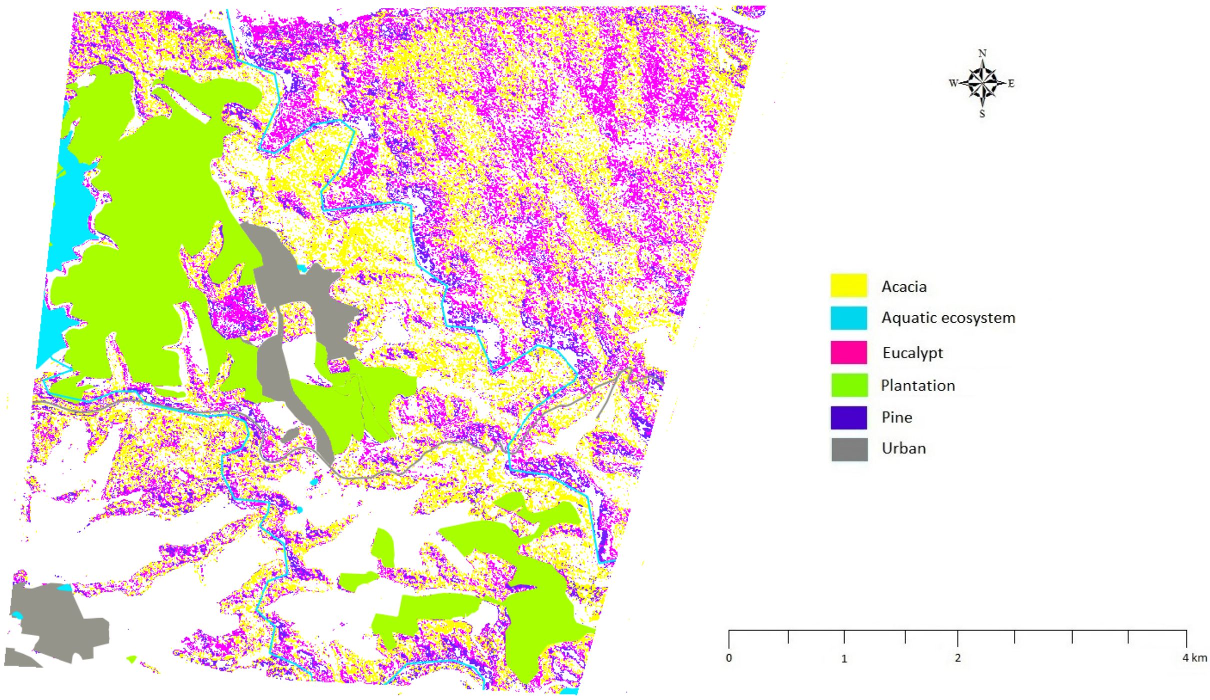

Figure 4.6. Invasive Acacia, Eucalyptus and Pinus trees detected by the SPOT-6 classification of the George and Wilderness area within the extent of the WV-3 data. Invasive trees are shown in relation to urban areas, plantations, aquatic ecosystems and roads.

Table 4.5. Confusion matrix resulting from the WV-3 classification, indicating the percentage of correctly classified pixels for each class in the diagonal grey cells. The Overall Accuracy (OA) is calculated as the average of the correctly classified pixels and given as a percentage. UA is the number of correctly classified test pixels divided by the total number of pixels in that class given as a percentage (i.e. the row total) and PA is the number of correctly classified pixels divided by the total number of pixels that should have been in that class given as a percentage (i.e. the column total) (Woodcock *et al.*, 2002). Row elements represent the percentage of ROIs from each class which were classified in each class and the columns show where the test ROIs for each class were placed by the classification.

Class	**Acacia**	**Agriculture**	**Aquatic ecosystem**	**Bare ground**	**Eucalypt**	**Fynbos**	**Indigenous forest**	**Pine**	**Urban**	**SUM**	**UA (%)**
Acacia	89.29	0.00	0.00	0.00	7.14	0.00	3.57	0.00	0.00	28	89.29
Agriculture	2.70	83.78	0.00	8.11	2.70	0.00	0.00	0.00	2.70	37	83.78
Aquatic ecosystem	0.00	0.00	88.89	0.00	0.00	0.00	11.11	0.00	0.00	45	88.89
Bare ground	0.00	18.00	0.00	74.00	0.00	0.00	0.00	0.00	8.00	50	74.00
Eucalyptus	17.39	0.00	0.00	0.00	63.04	0.00	6.52	13.04	0.00	46	63.04
Fynbos	2.33	0.00	0.00	0.00	6.98	81.40	6.98	2.33	0.00	43	81.40
Indigenous forest	13.16	0.00	0.00	0.00	2.63	13.16	60.53	10.53	0.00	38	60.53
Pine	0.00	0.00	0.00	0.00	10.53	0.00	13.16	76.32	0.00	38	76.32
Urban	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	35	100.00
SUM	40	40	40	40	40	40	40	40	40	360	
PA (%)	62.50	77.50	100.00	92.50	72.50	87.50	57.50	72.50	87.50		**OA = 78.89%**

Table 4.6. Comparison of overall, producer's and user's accuracies for the invasive tree classes in the classification of SPOT-6 and WV-3 data.

		Acacia	Eucalypt	Pine
SPOT-6 (Garden Route)	Area (Ha)	33.00	77.17	58.21 *
	Producer accuracy (%)	7.50	37.50	47.50
	User accuracy (%)	18.18	29.41	31.93
SPOT-6 (George and Wilderness)	Area (Ha)	82.95	85.77	28.41
	Producer accuracy (%)	72.00	30.00	48.00
	User accuracy (%)	62.07	39.47	52.17
WV-3	Area (Ha)	61.28	84.00	100.68
	Producer accuracy (%)	62.50	72.50	72.50
	User accuracy (%)	89.29	63.04	76.32

* Excluding the Plantation class, which was predominately pines (Area of the Plantation class was 80.01 Ha)

4.4 The prioritisation criteria for management of invasive tree species in the Garden Route

Combining the published findings of previous IAP management works produced a list of five applicable criteria for controlling invasive trees (Table 4.7). These criteria were 'Value of the land for water supply,' 'Invasion of IAPs,' 'Value of the land for biodiversity/Critical Biodiversity Areas (CBAs),' 'Existing management in place/Accessible areas' and 'Presence of endangered species.'

Assigning weights to criteria permits more realistic decision making. The criterion 'Value of the land for water supply' indicated areas which are important for water provision and was weighted 28.2%. Only one of the published studies included the 'Value of the land for water supply' as the highest priority, giving it a weighting of 45.7% (Van Wilgen *et al.*, 2008a). However, all six studies acknowledged its importance, albeit with varied weightings. The weight of the criterion ranged in value from 4.6% (Forsyth & Le Maitre, 2011) to approximately 10 time this amount (45.7%). Forsyth *et al.* (2012), Forsyth *et al.* (2015) and Van Wilgen *et al.* (2007) gave 'Value of the land for water supply' similar weightings of 22.3%, 25.6% and 25% respectively. Forsyth *et al.* (2009) gave this criterion a weighting of 12.1%. The 'Value of the land for water supply' was the top ranked criterion for IAP management and meant, in this study, aquatic ecosystems areas were included as the highest ranking priority areas.

'Invasion of IAPs' represents areas which have priority IAPs present or are vulnerable to invasion. This criterion was created by combining two criteria relating to IAP control, namely 'Presence of priority IAPs' and 'High potential invasion areas.' This merger occurred due to a lack of spatial data to represent both criteria in the subsequent SCP analysis. The weighting for 'Invasion of IAPs' was 24.4%, which consisted of 16.8 and 7.6% for 'Presence of priority IAPs' and 'High potential invasion areas' respectively. Five studies included the 'Presence of priority IAPs' criterion (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2009, 2012; Forsyth & Le Maitre, 2011) giving it weightings of 25, 14.3, 12.3, 17.3 and 11.6% respectively. 'High potential invasion areas' was included in three of the studies but it is given low rankings by Forsyth *et al.* (2015) (8.8%) and Forsyth and Le Maitre (2011) (2.8%). 'Invasion of IAPs' was the second highest weighted criterion for prioritising IAP management in the Garden Route.

The criterion 'Value of the land for biodiversity/CBAs' concerns areas which are important for conserving biodiversity and ecosystem function. The criterion was included in five of the six studies, which ensured it had the third highest ranking (21.4%). The values given for this criterion ranged from 10.4% (Forsyth *et al.*, 2012) to 26.6% (Forsyth & Le Maitre, 2011). Its weighting was fairly consistent, receiving 20.9, 18.1 and 26.4% by Van Wilgen *et al.* (2008a), Forsyth *et al.* (2009) and Forsyth *et al.* (2015).

'Existing management in place/Accessible areas' represents areas which are easy to manage, as this will likely improve the success of IAP control (Forsyth *et al.*, 2012). These are protected areas and areas on a slope <22.5°. The criterion had a weighting in this study of 19.8%. Both Forsyth *et al.* (2009) and Forsyth *et al.* (2012) ranked this criterion highly (49.1 and 42.2%), referring to it as the 'Ability of an area to remain clear of IAP's'. However, Forsyth and Le Maitre (2011) gave it 3.6% of the weighting and no other studies include it. However, Forsyth *et al.* (2015) do comment that it should be a consideration for IAP management in the GRNP.

The final criterion, 'Presence of endangered species,' represented areas which have endangered species present. Although the presence of endangered species does not always directly influence aquatic ecosystem function, it is a consideration for determining CBAs, and therefore is associated with the criterion 'Value of the land for biodiversity/CBAs.' The 'Presence of endangered species' was rated as the highest ranking criterion by Forsyth *et al.* (2015) but none of the other studies included it. It therefore averaged a low ranking (6.15%).

Five criteria were excluded as they do not relate to water and therefore were not applicable to this study. These were 'Tourism zones,' 'Importance of area for harvesting of resources,' 'Job creation potential/Impact on socio-economic risk,' 'Alignment with fire management plans' and 'Alignment with management plans.' One criterion, 'Experienced the largest habitat loss,' was eliminated as insufficient data were available to measure it.

The average weight of the criteria is shown in Table 4.7. The ‘Average weight of the six studies’ was calculated by finding the mean value of each criterion. For example, the average weight of the ‘Value of the land for water supply’ was (25.62 + 22.3 + 4.6 + 12.1 + 45.7 + 25) /6 = 22.55%. The ‘Average weight of each criterion used for this study’ was found by dividing the average weight of the criterion by the total of all the criteria’s mean values. For example, the average weight of the ‘Value of the land for water supply’ was 22.55/ (22.55 + 13.42 + 6.1 + 17.06 + 15.85 + 4.91) = 28.23%.

Table 4.7. Review-based criteria identified by previous literature for prioritising management of IAPs in the Garden Route which form the prioritisation criteria used in this study. The 'Average weight of the six studies' was calculated by finding the mean value of each criterion. For example, the average weight of the 'Value of the land for water supply' was (25.62 + 22.3 + 4.6 + 12.1 + 45.7 + 25) /6 = 22.55%. The 'Average weight of each criterion used for this study' was found by dividing the average weight of the criterion by the total of all the criteria's mean values. For example, the average weight of the 'Value of the land for water supply' was 22.55/ (22.55 + 13.42 + 6.1 + 17.06 + 15.85 + 4.91) = 28.23%.

Criteria	**Study (% weight of criteria)**						**Average weight of the 6 studies (%)**	**Average weight of criterion used for this study (%)**
	Forsyth *et al.* (2015)	Forsyth *et al.* (2012)	Forsyth & Le Maitre (2011)	Forsyth *et al.* (2009)	Van Wilgen *et al.* (2008a)	Van Wilgen *et al.* (2007)		
Value of the land for water supply	25.62	22.3	4.6	12.1	45.7	25	**22.55**	**28.23**
Presence of priority IAPs^		17.3	11.6	12.3	14.3	25	**13.42**	**(16.80 + 7.63)**
High potential invasion areas	8.79		2.8			25	**6.10**	**24.43◊**
Value of the land for biodiversity/Critical Biodiversity Areas	26.34	10.4	26.6	18.1	20.9		**17.06**	**21.35**
Existing management in place/Accessible areas	*	42.4	3.6	49.1			**15.85**	**19.84**
Presence of endangered species ▫	29.47						**4.91**	**6.15**
						Total	**79.89**	**100**
Excluded Criteria								
Tourism zone ᐞ	5.07		15.3				**3.40**	**0.00**
Importance of area for harvesting of resources ᐞ		3.7			4.8		**1.42**	**0.00**
Job creation potential/Impact on socio-economic risk ᐞ		3.8	15.1	4.4	14.3		**6.27**	**0.00**
Alignment with fire management plans ᐞ			5.9	4.1			**1.67**	**0.00**
Alignment with management plans ᐞ			14.5				**2.42**	**0.00**
Experienced the largest habitat loss•						25	**4.17**	**0.00**

^ As defined by each study

◊ 'Presence of priority IAPs' and 'High potential invasion areas' criteria were combined to create one criterion called 'Invasion of IAPs'

▫ Included as it is used in the identification of CBAs

* Alignment with existing management plans is noted by the authors as important but is not included as a criterion

ᐞ Excluded as socio-economic

• Excluded as insufficient data available to measure

4.5 Priority areas for invasive tree species control in the Garden Route

To prioritise the Garden Route for invasive tree management, an SCP analysis was performed. Spatial datasets representing the prioritisation criteria for this study were input into the SCP software, Zonation (Figure 4.7). Figures depicting the datasets used are shown in Appendices 2-9. Plantations and urban areas were masked for the analysis and are therefore shown (in Figure 4.7) as grey. The highest priority areas were coloured red and include the majority of the Wilderness and Knysna sections of the GRNP, most notably the Wilderness Lake System, Knysna Estuary and Knysna Forest (see Figure 4.1 for orientation). The coastal section between Nature's Valley and Eersterivierstrand was also highlighted as a priority for invasive tree management, excluding a thin strip next to the ocean which represented sand.

Throughout the Garden Route, rivers were identified as a high priority for invasive tree management. This can be attributed to two of the criteria concerning them, namely 'Value of the land for water' and 'Invasion of IAPs' (i.e. disturbed areas). Of the rivers included in the analysis, 100% were of the highest priority for management, meaning they were ranked in the top 20% of priority areas.

Of the protected areas, the GRNP was a higher priority than others. Approximately 16.7% of the park was found to be of the highest management priority whereas only 10.1% of the other protected areas were prioritised as highly. This was most likely a result of the park containing more disturbed areas and fewer upland areas.

The upland sections of the Tsitsikamma section of the GRNP were designated as a lower priority than other sections of the park, as indicated by the blue and purple regions in Figure 4.7. The northern extent of the Garden Route was also low priority, owing to the steepness of the slope and lack of areas important for water supply or biodiversity. Disturbed areas, such as riparian zones, roadsides and plantation boundaries were shown as a high priority for management.

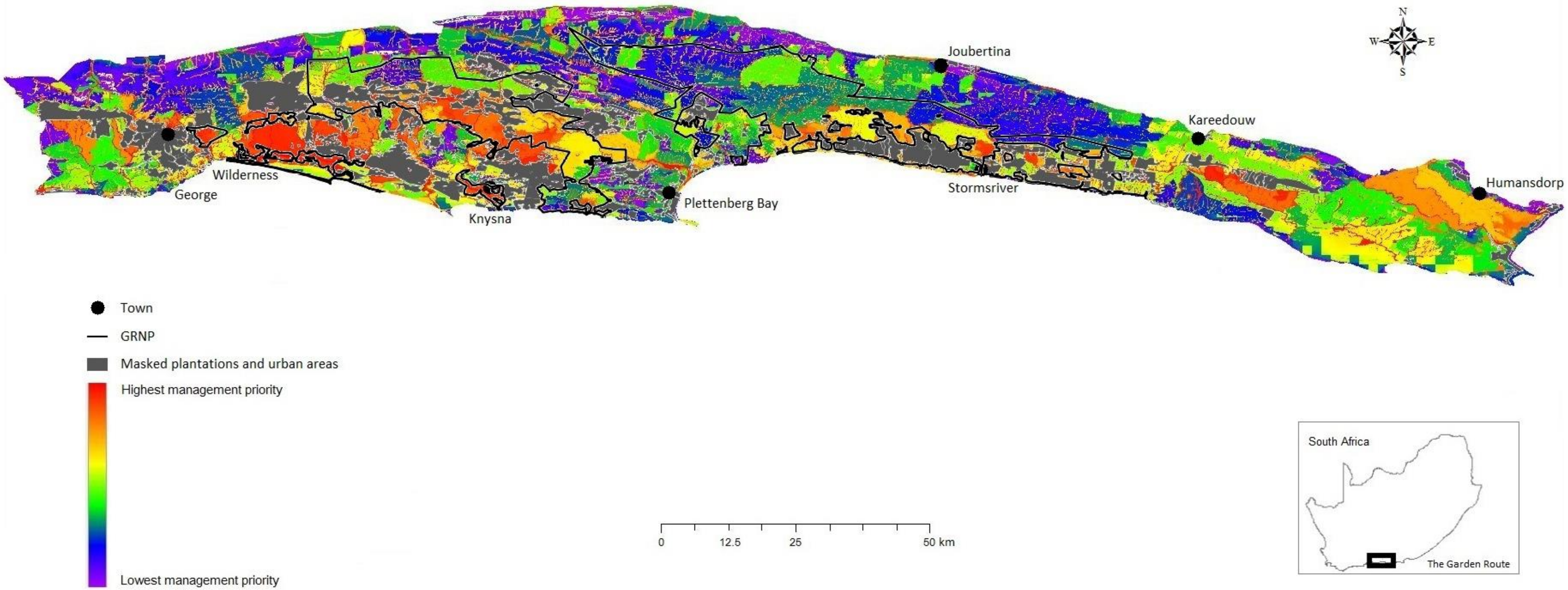

Figure 4.7. The results of prioritising invasive tree management in the Garden Route, created using SCP software and spatial data relevant to the management criteria shown in Table 4.7. Urban areas and plantations were masked and are of the lowest management priority (shown in grey).

4.6 Summary of results

To determine which areas in the Garden Route should be prioritised for invasive tree species management, this study first identified priority species and areas vulnerable to IAP invasion, then applied prioritisation criteria to the Garden Route. Eight priority tree species were identified and SPOT-6 and WV-3 data used to detect them. Priority species were *Acacia cyclops* (rooikrans), *Acacia longifolia* (long-leaved wattle), *Acacia mearnsii* (black wattle), *Acacia melanoxylon* (blackwood), *Acacia saligna* (Port Jackson willow), *Eucalyptus camaldulensis* (red river gum), *Pinus pinaster* (cluster pine) and *Pinus radiata* (radiata pine). The OAs of the SPOT-6 classifications (40.8% for classification of the Garden Route and 62.5% for the classification of the George and Wilderness area) was lower than the target accuracy of acceptable use (70%), however the OA of the WV-3 data exceeded this target by 9 percentile points.

To identify priority areas in the Garden Route for IAP control, five criteria were found which were applicable to preserving aquatic ecosystems and their function and these were applied to the study area using SCP software. These criteria were the 'Value of the land for water supply,' 'Invasion by IAPs,' 'Value of the land for biodiversity,' 'Existing management in place/accessible areas' and the 'Presence of endangered species.' The results of this analysis indicated the highest priority areas for invasive tree management are the: Saasveld section of the GRNP, Wilderness Lakes, Knysna Forest, Knysna Estuary, Tsitsikamma Forest around Stormsriver and a disturbed area of fynbos southeast of Kareedouw. The following chapter (Chapter 5) will discuss these results.

Chapter 5 Discussion

This chapter expands on the results from Chapter 4 and discusses how well the study's objectives (Section 1.7) were met. It includes a discussion of prioritising invasive tree species and spatially locating them, including the process of capturing the Regions of Interest (ROIs) and the subsequent Random Forest (RF) classifications of the *Satellite Pour l'Observation de la Terre-6* (SPOT-6) and WorldView-3 (WV-3) data. The results of the Spatial Conservation Planning (SCP) analysis using invasive tree management criteria are discussed and compared with other published findings. The chapter then highlights the limitations of this study, makes recommendations for further research, and finishes with a conclusion.

5.1 The Suitability of the focal invasive tree species for the Garden Route

Invasive Alien Plants (IAPs) are a significant problem in the Garden Route National Park (GRNP) (Forsyth & Le Maitre, 2011). Therefore the first research objective was to spatially locate invasive tree species in the Garden Route. First, this required identifying the most problematic invasive tree species. As many studies have been published on IAPs in the Garden Route, it was necessary to focus on literature listing the tree species with the most detrimental effects on water flow and aquatic ecosystems (Van Wilgen *et al.*, 2008b) and with the ability to transform their habitat (Richardson & Van Wilgen, 2004).

Seven published studies provided criteria to identify the most problematic species for aquatic ecosystems and their associated services. These criteria identified: transformer species, priority species for riparian zones, priority for removing these species from rivers, species which affects fynbos and surface water, priority species for fynbos, priority species for the GRNP and National Environmental Management Biodiversity Act (NEMBA) Category 1b invasives. The results of the analysis found eight focal invasive tree species for further analysis. The species were *Acacia cyclops* (rooikrans), *A. longifolia* (long-leaved wattle), *A. mearnsii* (black wattle), *A. melanoxylon* (blackwood), *A. saligna* (Port Jackson willow), *Eucalyptus camaldulensis* (red river gum), *Pinus pinaster* (cluster pine) and *P. radiata* (radiata pine). All eight of these species were listed as priorities by Van Wilgen *et al.* (2008b) and Forsyth and Le Maitre (2011), indicating these species' significance for IAP control in the Garden Route and aquatic ecosystems.

Whilst many previous prioritisation studies produced a more comprehensive list of species, the inclusion of too many priorities would impede management. Eight priority species were identified, which compared favourably with the nine priority species identified by Forsyth *et al.* (2012) for the fynbos biome. As the previous studies used different prioritisation methods, for example based on area (e.g. the GRNP, (Forsyth & Le Maitre, 2011)), impacts (e.g. transformer status (Baard & Kraaij, 2014)) or by habitat (e.g. riparian zones (Forsyth *et al.*, 2012)), combining them ensured the most important priority species for aquatic ecosystems in the Garden Route were included.

The similarities between the focal species in various prioritisation studies indicate the significance of these species as the worst invaders in the Garden Route. In South Africa, wattles, gum and pines trees have been recognised as being problematic for aquatic ecosystems (Le Maitre *et al.*, 2000). Hence the inclusion of these three genera in this study was expected. One species, *Acacia melanoxylon,* is recognised as one of the most prevalent IAPs (Dennill & Donnelly, 1991; SANParks, 2014) and it was therefore expected to be a priority in more than four of the seven published priority species lists used in this study. As *A. melanoxylon* invades riparian zones (Richardson & Kluge, 2008; Baard & Kraaij, 2014), it was surprising that it was not included as a priority for rivers by Van Wilgen *et al.* (2007) or for riparian zones by Forsyth *et al.* (2012). This could be due to its abundance being underestimated, owing to the difficulty in detecting it using remote sensing or it forming small, isolated canopies. Despite *A. melanoxylon* being excluded by some studies, it is still an invasive species in the Garden Route which should be prioritised for management and was therefore included in this study.

The inclusion of only one eucalypt species, *Eucalyptus camaldulensis*, as a priority by this study was unexpected because eucalypts are regularly noted as having detrimental effects on aquatic ecosystems (Forsyth *et al.*, 2004; Driver *et al.*, 2012). They use large amounts of water and can cause intense fires due to them containing flammable oils (Driver *et al.*, 2012). However, their multiple uses, such as for honey production, timber and fuel (Driver *et al.*, 2012), may explain why they have been excluded from many priority species lists. Furthermore, although *Eucalyptus camaldulensis* is a transformer in South Africa (Henderson, 2001), this species and *E. diversicolor* (Karri gum) are not transformers in the Garden Route (Baard & Kraaij, 2014). Eucalypts have been incorrectly classified as invasive when in fact they are naturalised (Richardson *et al.*, 2000) and this misconception may account for discrepancies in the literature.

Some species, which were identified as a priority by other studies, were excluded by this analysis. Notably, *Populus x. canescens* (grey poplar) was included by five of the existing priority species lists (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008a; Van Wilgen *et al.*, 2008b; Forsyth & Le Maitre, 2011; Forsyth *et al.*, 2012). Whilst many studies note the prominence of grey poplars, particularly in riparian zones (Henderson, 2007; Van Wilgen *et al.*, 2012), very few note them having any major environmentally detrimental impacts. The species has been identified as a transformer species elsewhere in South Africa (Henderson, 2001) but it was not identified as one in the Garden Route (Baard & Kraaij, 2014). Therefore, poplars were excluded as a priority species by this study and others.

This study focused on prioritising invasive tree species, therefore other growth forms were outside the scope. There are some species which met all the criteria (i.e. being transformers, reduced water flow and be included by at least two other studies) but were excluded from this study as they were not trees. For example, the shrub *Hakea sericea* (silky hakea) is a transformer (Baard & Kraaij, 2014), invades riparian zones (Forsyth *et al.*, 2012) and was listed as a priority in four other studies (Van Wilgen *et al.*, 2007; Van Wilgen *et al.*, 2008a; Van Wilgen *et al.*, 2008b; Forsyth & Le Maitre, 2011). However, owing to the negative effects of invasive trees on aquatic ecosystems (see Section 2.5.2), trees are therefore a higher priority for management. The location of the eight focal tree species were subsequently mapped using the RF classification using multispectral data.

5.2 Evaluating the suitability of multispectral data for classifying invasive tree species

In this study, the results of the SPOT-6 classifications achieved overall accuracies (OAs) below the 70% target. OA of the SPOT-6 classification of the Garden Route was 40.8% and for the George and Wilderness area it was 62.5%. The increase in percentile points between the classifications was the result of an increase in the number of ROIs across the extent of the data and the removal of the Plantation class.

The accuracies of the SPOT-6 classifications were compared to those of Forsyth *et al.* (2014), who used SPOT-6 to classify *Pinus* species in the Western Cape. The results of Forsyth *et al.* (2014)'s classification achieved higher accuracies than this study. Their producer's accuracy (PA) was 70% (22 percentile points higher than the Pine class in this study) and their user's accuracy (UA) was 97.2% (45 percentile points higher than this study). Their higher values were most likely due the isolation of the canopies, there being fewer tree classes to distinguish among and due to a fire altering soil reflectance in non-*Pinus* areas and encouraging new vegetation growth (Forsyth *et al.*, 2014). However, Forsyth *et al.* (2014) acknowledge that these levels of accuracy were only possible because the canopy size exceeded SPOT-6's resolution and, in other areas, higher spatial resolution data may be needed.

To separate the tree classes in this study, higher resolution data were sought. The WV-3 data obtained for this study were classified with an OA of 78.9%, which is comparable with similar research. Using

WV-2 data and the RF classifier, Immitzer *et al.* (2012) detected *Pinus sylvestris* (Scots pine) in Austrian forests during summer with a PA of 77.9% and a UA of 76.3%. Similarly in this study, for the Pine class PA was 72.5% and UA was 76.3%. Also using WV-2 data, Peerbhay *et al.* (2013) were able to detect *Acacia mearnsii*, *Eucalyptus grandis* (rose gum), *E. nitens* (shining gum), *E. smithii* (gully gum), *Pinus elliottii* (slash pine) and *P. patula* in closed canopy forests in KwaZulu-Natal, South Africa, with an OA of 85.4%. A further study (Cho *et al.*, 2015) was able to separate *Acacia* species (predominately *A. karroo*) from other trees in closed canopy forests in KwaZulu-Natal, South Africa during summer, with a PA of 95.4 and a UA of 92.4%. Although this study's accuracy was lower than the results of Peerbhay *et al.* (2013) and Cho *et al.* (2015), the OA (78.9%) was still above the target of 70%. This study therefore concurs with Peerbhay *et al.* (2013), Cho *et al.* (2015) and Immitzer *et al.* (2012) that WV data can be used to effectively map invasive trees.

5.2.1 Sources of inaccuracy for the classifications of multispectral data

Confusion between the classes was a source of error in both the SPOT-6 and WV-3 classifications. Class mixing between the Indigenous forest and three invasive tree classes was particularly high for the SPOT-6 classifications, as demonstrated in the confusion matrixes (see Tables 4.3 and 4.4). For the WV-3 classification, these errors were lower (see Table 4.5) but were present nevertheless. The confusion can be attributed to the complex forest structure of the Garden Route (Immitzer *et al.*, 2012), the tree canopy sizes and the tree classes having similar spectral signatures. The addition of the red edge and yellow bands in the WV-3 data allowed for better separation of the tree classes. Therefore, data with these bands are recommended for successfully classifying tree species in the Garden Route.

The size of the ROIs captured for a classification is a key determinant in the accuracy of separating invasive trees (Foody & Mathur, 2006). The initial SPOT-6 classification of the Garden Route used ROIs which were four pixels, which represented an area of 24 m^2. Using four pixels meant many of the GPS points for the invasive tree classes could not be used because the diameter of the canopies (typically 2-3 m) was not compatible with an area this large. Within the study area, the trees often occurred as single individuals or in narrow rows, meaning they were smaller than one pixel. As a result, parts of the study area were not represented in the classification. This meant, for the SPOT-6 classifications, the spectral signature of the invasive tree ROIs did not represent that of the trees across the entire study domain. This therefore reduced the accuracy of the classification.

For the WV-3 classification, the ROIs were four pixels, which represented 4.96 m^2 per class. Using ROIs this size ensured a balance between the ROIs' ability to capture the range in a class' reflectance values and a sufficient number of GPS points being included in the classification (Immitzer *et al.*, 2012). As a result, this contributed to the higher levels of accuracy achieved by the WV-3 classification than for the SPOT-6 classifications.

The representativeness of the ROIs heavily influences the accuracy of a classification (Foody & Mathur, 2006). For this study, ROIs for the invasive tree classes were predominately captured based on GPS points of known focal invasive tree populations. The points were unevenly and opportunistically spread in the study domain, to enable optimal use of accessible sites. Trees next to the roadside were favoured due to easy access but consequently many of the GPS points captured were subject to influence by the road (Urban class). Even when single-pixel ROIs were used (for the SPOT-6 classification of the George and Wilderness area), the invasive tree classes were still subject to interference from the surrounding land classes as a result of the canopy architecture and shape. This meant the reflectance values of the invasive tree pixels were altered and were therefore more difficult to classify correctly (Foody & Mathur, 2006; Ollinger, 2011). Although this demonstrates how accessible areas are easier to manage, it also shows a bias in selecting the sites for the ROIs, one that should be addressed in further studies.

5.2.2 Summary of the suitability of SPOT-6 and WorldView-3 Data for classifying invasive tree species in the Garden Route

The strengths and weakness of different multispectral data indicate the suitability to purpose. Those found in this study for the SPOT-6 and WV-3 data are show in Table 5.1. The principal advantages of WV-3 data over SPOT-6 were that WV-3 could detect and separate invasive tree species. However, SPOT data remains affordable, hence other ways to improve the classification should be investigated for SPOT-6 (see Sections 5.5 and 5.6).

Table 5.1. A comparison of the SPOT-6 and WorldView-3 data, identifying the strengths and weaknesses of the two types of imagery found by this study.

Data	Strengths	Weaknesses
SPOT-6	Can successfully detect aquatic ecosystems and urban areas Cost affordable - often free through the South African National Space Agency (SANSA) for South Africans	Four bands are unable to discriminate between tree species owing to lack of the red edge band Spatial resolution too coarse for detecting trees with canopies which has a diameter below 3 m The data cannot effectively separate the invasive *Acacia, Eucalyptus* and *Pinus* species in the Garden Route
WV-3	Eight bands are able to positively identify invasive trees particularly owing to the red edge band and the yellow band Resolution (1.24 m^2) is sufficient for detecting invasive trees with canopies < 3 m in diameter The data can successfully detect other land classes, such as aquatic ecosystems and urban areas	Costly (retail price is US$22.50 for 1 km^2 (Apollo Mapping, 2016))

The results of this study show that whilst SPOT-6 multispectral data were able to classify aquatic ecosystems and urban areas in the Garden Route with reasonable success (see Tables 4.3 and 4.4), the data were unable to locate any of the focal tree species. It is therefore concluded that SPOT-6 is ineffective for separating *Acacia*, *Eucalyptus* and *Pinus* species in the Garden Route.

Although WV-3 is capable of separating invasive trees in the Garden Route, the data are unlikely to be suitable for IAP management either. The WV-3 data in this study were freely available for a 25 km^2 area and therefore did not cover the entire Garden Route and could not be used to locate the priority tree species throughout. Owing to the retail price of WV-3 data (US$22.50 for 1 km^2 (Apollo Mapping, 2016)) and the size of the Garden Route (approximately 6,100 km^2), the use of WV-3 data is not an option. However, because WV-3 can separate tree species better than SPOT-6, the data could nevertheless be useful for smaller areas. Although unable to spatially locate invasive tree species throughout the Garden Route as intended, this study was able to identify multispectral data that could be used for detecting invasive trees and used existing spatial datasets to predict the likely distribution of the focal species.

5.3 The Suitability of spatial conservation planning software for invasive tree management in the Garden Route

As resources are limited for IAP control in South Africa and the Garden Route (Forsyth *et al.*, 2009; De Lange & Van Wilgen, 2010), the final research objective was to apply the prioritisation criteria to identify priority aquatic ecosystems for invasive tree species management. This was attained by inputting the criteria into SCP software to create a prioritisation map across the landscape.

SCP software proved to be a useful tool for IAP management. Previous prioritisation studies in the Garden Route have used quaternary catchments (Forsyth *et al.*, 2009) or man-made boundaries to indicate priority areas. For example, Forsyth *et al.* (2015) prioritised the GRNP based on the 2,808 management compartments used by SANParks to divide and manage the park. Another approach (Forsyth *et al.*, 2009) involved the integration of priority species with the management priorities for Western Cape catchments. Both these studies used the Analytic Hierarchy Process (AHP) to develop prioritisation rankings. Although these methods are possible ways to derive priorities, it is more difficult to consider variables which are not specific to catchments, such as rivers. However, these factors can be included by SCP software, such as Zonation. SCP software is therefore an effective prioritisation tool.

5.3.1 Evaluating the spatial conservation planning criteria

The second objective of this study was to formulate prioritisation criteria for the management of invasive tree species in aquatic ecosystems. This was achieved by examining published studies on prioritising IAPs and combining the relevant results into one set of criteria. Previous literature and discussions with potential workshop participants indicated that sufficient work on the prioritisation and management of IAP species already existed and consequently a workshop would be an inefficient use of time and resources.

Social criteria were included by five of the six previous prioritisation studies. Of these, four included 'Job creation potential/Impact on socio-economic risk' as a criterion for IAP management (Van Wilgen *et al.*, 2008a; Forsyth *et al.*, 2009, 2012; Forsyth & Le Maitre, 2011). The majority of the weightings for these social criteria were low (see Table 4.7), which implies such criteria are less important for managing IAPs and aquatic ecosystems. However, the inclusion of social criteria can be questioned, as these do not necessarily help to control IAPs or safeguard aquatic ecosystems (Van Wilgen & Wannenburgh, 2016). Often IAP management includes aims and objectives which might conflict with conservation, such as poverty relief or reducing unemployment (Van Wilgen *et al.*, 2008b). For IAP control, such benefits should be a bonus, not a consideration, when devising a management plan (Van Wilgen & Wannenburgh, 2016).

The criterion prioritising areas which 'Experienced the largest habitat loss' (Van Wilgen *et al.*, 2007) was excluded from this study. This was due to a lack of appropriate spatial data to represent it in the

SCP analysis. Although this highlights a shortcoming of the current data for the Garden Route, this criterion is unlikely to be of high importance for the Garden Route nonetheless, as it is the quality of the habitat for aquatic ecosystems and their services which are more important (Rountree *et al.*, 2009). Because this criterion was only included by one of the six published criteria lists (Van Wilgen *et al.*, 2007), this indicates it is of low importance for IAP management.

Analysing the results of published prioritisation studies meant that several authors (namely Forsyth, G.G., Le Maitre, D.C. and van Wilgen, B.W.) contributed to multiple studies used for prioritisation in this study. For studies in which experts produced management criteria (Forsyth *et al.*, 2009, 2012; Forsyth & Le Maitre, 2011), the authors merely facilitated the workshops and did not participate themselves. Although this is a potential source of bias, these authors are prominent researchers on IAP management in the Garden Route, and therefore their contribution to several prioritisation studies was likely. By including all applicable results of the studies, analysis concerning area-based prioritisation approaches, such as prioritising the Garden Route, was combined with prioritisation focusing on ecosystems, such as rivers. Therefore, including all these results ensured no vital consideration was omitted, and the criteria for this study were suitable for prioritising management of IAPs in aquatic ecosystems in the Garden Route.

5.3.2 Evaluating the spatial conservation planning results

Upland and mountainous areas (Figure 3.8) were a low priority for invasive tree management in this study. These sections have reduced accessibility and in the Garden Route, these areas contain fewer CBAs, protected areas or disturbed habitats. However, the SCP results indicated that the riparian zones in these areas are still of high priority (Figure 4.7). The riparian zones were ranked highly as they are important for freshwater supply and controlling the spread of IAPs. As the effects of invasive trees on water supply can be felt downstream, such as through a reduction in water supply or the accumulation of seeds (Hood & Naiman, 2000; Le Maitre *et al.*, 2000; Zedler & Kercher, 2004), it is vital these areas are managed, despite their limited accessibility.

In the GRNP, the Tsitsikamma section was the lowest priority for invasive tree management. This maybe because it has fewer disturbed areas than other sections. As Tsitsikamma is a protected area, it was anticipated that it would be a higher priority than the coastal section between Nature's Valley and Eersterivierstrand (Figure 4.1), yet the results indicated that this coastal area was a higher priority for management. The area between Nature's Valley and Eersterivierstrand has no formal protection, unlike other high priority areas, such as the Wilderness Lakes and Knysna Estuary. The area is predominately fynbos and plantations (Figure 4.1), with minimal urban development. This section of the Garden Route is a Strategic Water Source Area (SWSA) and consists of many disturbed habitats, such as roadsides, rivers and plantation boundaries, and was consequently ranked highly. As plantation management can conflict with invasive tree control (Richardson, 1998; Richardson & Van Wilgen, 2004), this should be accounted for when implementing an invasive tree management strategy for the Garden Route.

5.3.3 Comparing the spatial conservation planning results to published research

Of the six studies which provided the prioritisation criteria used in this study (see Table 2.4), two (Forsyth *et al.*, 2009, 2015) applied their results to their respective study areas (Figures 5.1 and 5.2). Although these studies had differing extents, their results were compared to the results of this research (Figure 5.3). Owing to the differing goals of the prioritisation studies used to derive the criteria, averaging their criterial weightings may have been questioned by some. However, as all the prioritisation studies shared a common goal to control IAPs and were relevant to invasive tree control in the Garden Route, it was considered an acceptable approach.

The importance of maintaining aquatic ecosystems' health is consistently noted by researchers in the Garden Route and South Africa (see Section 2.4). This study therefore prioritised these habitats highly, not unlike Forsyth *et al.* (2015). The results of this study and those of Forsyth *et al.* (2015) indicated the areas around Sedgefield (Figure 1.3) as a high priority, along with the nearby Wilderness Lakes and Knysna Estuary. However, these sites were considered a low priority by Forsyth *et al.* (2009). Although Forsyth *et al.* (2009) prioritised the Wilderness catchment highly, they ranked the Knysna catchment (including the Knysna Estuary) low. This discrepancy between the studies' results can be attributed to Forsyth *et al.* (2009) prioritising mountainous areas over lowland regions. The mountainous areas around Kurland (Figure 4.1) are given high prioritisation scores by both Forsyth *et al.* (2009) and Forsyth *et al.* (2015) for the same reason. Although these areas are important for IAP management, clearing aquatic ecosystems is more important for controlling the focal species in this study.

The discrepancies between the studies' results are a consequence of various factors. These include the different; criteria, weightings, spatial data used to represent the criteria and prioritisation methods used (for example AHP or Zonation). The differences between the criteria and weightings used by the prioritisation studies are discussed in Section 4.4 and the differences between the methods are discussed at the beginning of Section 5.3.

The influence of the spatial data on the prioritisation results is evident in the prioritisation studies. This study, Forsyth *et al.* (2015) and Forsyth *et al.* (2009) all included the criterion 'Value of the land for water' but used different spatial data to represent it. In this study, the criterion was represented by the National Wetland Map 5 (Van Deventer, 2016a) and SWSAs (SANBI, 2013). Fosyth *et al.* (2015) used the Groundwater Resource Assessment II (DWAF, 2005) to indicate areas of high water yield, whilst Forsyth *et al.* (2009) represented this criterion using data of the same year from the Water Research Commission (Forsyth *et al.*, 2009). These data differ in how the criterion 'Value of the land for water' was defined. This could in part explain the discrepancies between the outputs generated by the analyses.

The data used to represent the criterion 'Value of the land for biodiversity' varied between the different prioritisation studies. In both this study and Forsyth *et al.* (2015), the criterion was represented by CBA data (SANBI, 2010d). However, in Forsyth *et al.* (2009), this criterion was represented by the vegetation types rated as 'Critically endangered', 'Endangered' or 'Vulnerable' by the National Vegetation Map (Mucina and Rutherford, 2006). This approach is based on the threat status of vegetation types whereas CBAs are areas which should be preserved to support rare species (Holness *et al.*, 2010), meaning the rarity of the vegetation is not the only consideration. The different representation of the criterion by the studies is another factor which influenced the results.

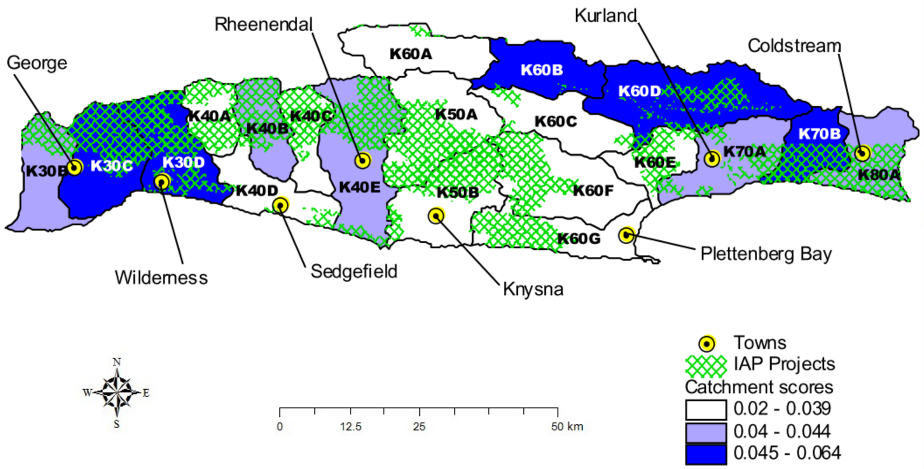

Figure 5.1. The results of Forsyth *et al.* (2009) identifying the priorities for IAP management in the GRNP by management compartments. Adapted from Forsyth *et al.* (2009).

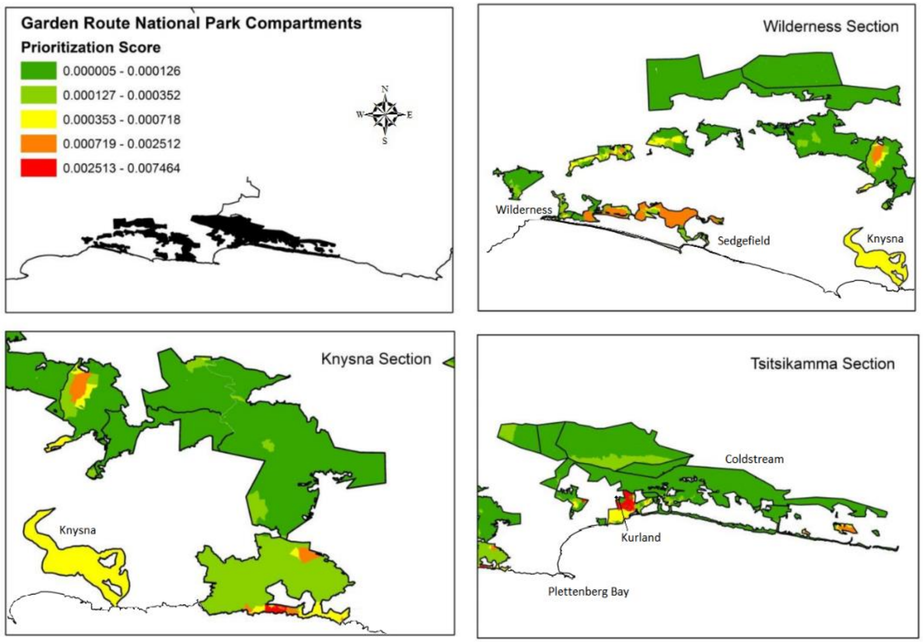

Figure 5.2. The results of Forsyth *et al.* (2015) indicating priority quaternary catchments in the Garden Route. A higher score shows a higher priority for managing IAPs. Adapted from Forsyth *et al.* (2015).

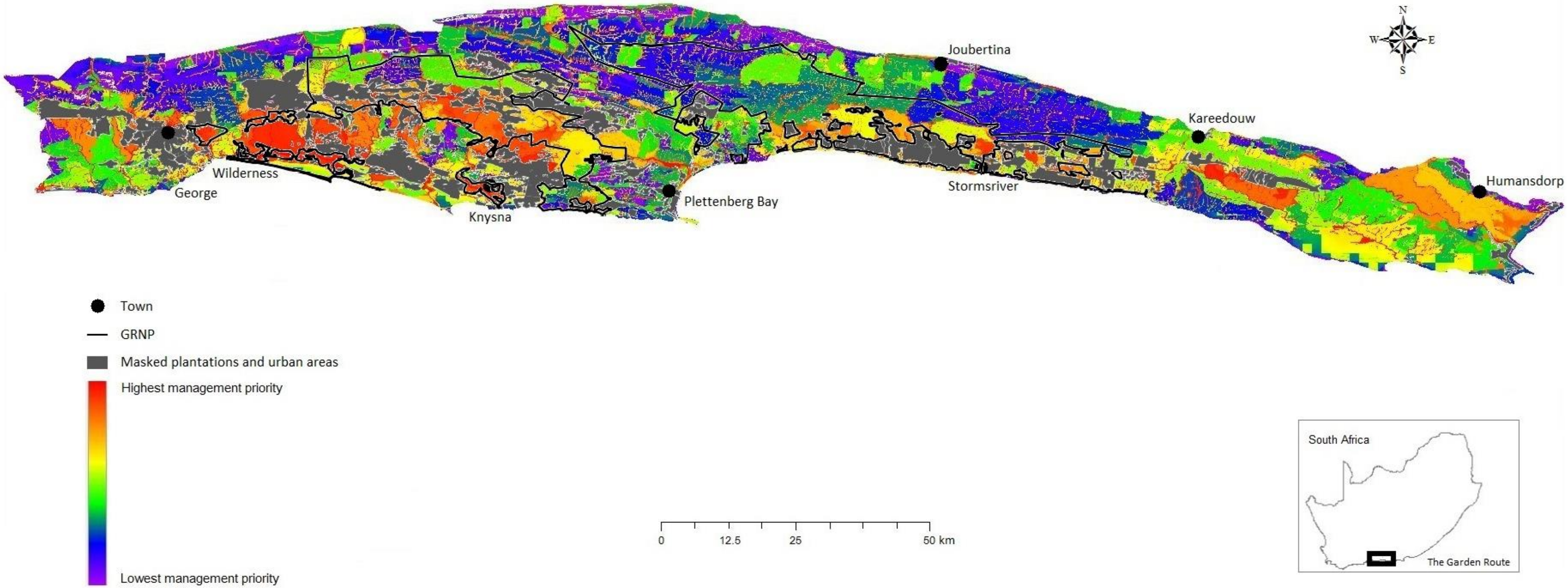

Figure 5.3. The results from this study prioritising invasive tree management in the Garden Route. For a description of how these results were generated, including the spatial data used and the invasive tree management criteria they represent, see Section 3.8.

5.3.4 Shortcomings of the spatial conservation planning analysis

An SCP analysis is limited by the accuracy of the input spatial datasets (Forsyth *et al.*, 2009) (see Appendices 3-10 for maps of the input spatial datasets). For this study, accurate datasets were not available for all the criteria (see Van Wilgen *et al.*, 2008b). As the limitations of several of these datasets have been identified (see Table 3.3), this indicates the reliance of prioritisation works on accurate spatial data and reiterates that Zonation, and AHP are decision support tools, not decision making tools (Lehtomäki *et al.*, 2016). The SCP output is also influenced by the user's choice of data to represent each criterion. Despite these limitations, it is still a time and cost-effective method for analysing management strategies in an area the size of the Garden Route (see Moilanen *et al.*, 2014).

5.4 Management implications and recommendations

Due to the GRNP's IAP problem (Baard & Kraaij, 2014), an appropriate strategy is required to address the issue. Alignment with current management plans is therefore a vital consideration for any IAP control plan (Forsyth *et al.*, 2015). The approach of the park notes the importance of conserving aquatic ecosystems and protecting the biodiversity there (SANParks, 2012, 2014). This aligns with three of the criteria in this study (see Table 4.7), namely 'Value of the land for water,' 'Value of the land for biodiversity/CBAs' and 'Presence of endangered species.'

As this study's criteria are compatible with the GRNP's IAP strategy, the results of the SCP analysis can be applied to the park. Both the management plan for the GRNP (SANParks, 2014) and this study acknowledge the importance of controlling IAPs and rehabilitating disturbed areas (referred to in this study using the criterion 'Invasion of IAPs'). The extent of the WV-3 data covered a portion of the GRNP (Figure 3.5) and therefore the results of the classification can be applied to invasive tree management there. The SCP analysis identified this section as a high priority for invasive tree management (Figure 3.5) so it is therefore recommended that the area is addressed for invasive tree management.

Mountainous areas were excluded from the analysis because they cannot be cleared without trained teams or specialised equipment and therefore require different management to other areas (Mudau, 2016). However, these areas are still important for IAP control as they receive the highest amount of rain and consequently the reductions to runoff caused by IAP invasions are more pronounced here (Le Maitre *et al.*, 2000). It is therefore acknowledged that these areas should still be managed in order to combat the problem of IAPs in the Garden Route.

The IAP strategy for the GRNP currently divides the land into compartments for management (Forsyth *et al*., 2015). The SCP results identified priority areas with shapes which do not fit these sections and may therefore prove difficult to manage using the current approach. If necessary, this can be overcome by averaging the SCP results over the existing management compartments to indicate the sections which have the highest priority.

5.5 Research implications

This study found SPOT-6 was not suitable for invasive tree detection. However, the accuracy of remote sensing classifications can be improved by obtaining larger ROIs across the study site to better capture the reflectance range of a land class. These ROIs should be subject to minimal edge effects from surrounding classes. In order to do this, a large number of GPS points of known invasive trees should be obtained, each with a canopy size surpassing the pixel size of the multispectral data. The availability of higher resolution spatial data for the entire Garden Route would also contribute to achieving higher levels of accuracy in a classification. These results can then be used in conjunction with an SCP analysis to indicate priority areas for invasive tree control in the Garden Route.

5.6 Recommendations for further study

The results of this study highlight a number of areas for further research. As SPOT-6 and WV-3 data were unsuitable for detecting trees in the Garden Route (SPOT-6 due to inadequate spatial resolution and insufficient bands and WV-3 due to cost), it is recommended that the suitability of other multispectral data be tested. To locate *Acacias*, *Eucalyptus* and *Pinus* trees in the Garden Route, a suitable sensor must have a spatial resolution finer than the canopy diameter (2-3 m) and bands which sufficiently cover the parts of the electromagnetic spectrum necessary to separate the focal species. For these species, this includes the red edge and yellow bands.

As the attempts to improve the SPOT-6 classification in this study were reasonably successful, further attempts to increase the accuracy of classifying SPOT-6 data could be tested. The SPOT-6 data acquired for this study were captured in the autumn and winter (i.e. between April and June) (see Table 3.1). Therefore, data captured in the spring and summer months could be classified to see if it is more effective at separating tree species. However, it is worth remembering that the accuracies will unlikely be comparable with those achieved with WV-3 data, owing to the limitations of the spectral and spatial resolution of SPOT-6 data identified by this study.

Since the cost of WV-3 data constrained its application in this study, the suitability of other less-expensive sensors can be investigated. The suitability of data with red edge and yellow bands is acknowledged, as these were advantageous for separating the tree classes in this study. Data with a spatial resolution less than the canopy size of a typical full-grown *Acacia*, *Eucalyptus* or *Pinus* tree may also be better at separating the species than SPOT-6. Should suitable and affordable multispectral data be found, remote sensing techniques can be used to locate focal species every few years to indicate the change in priority species' distribution (Rowlinson *et al.*, 1999).

To combat the problem of IAPs, accurate and current spatial data for biogeographical data in the Garden Route would be beneficial. Spatial data concerning priority invasive tree species location is of particular importance. In this study, such data would have helped in the capturing of ROIs, which would have likely improved the accuracy of the RF classifications. This data would have also improved the results of the SCP analysis. As the results of an SCP analysis are only as useful as the input spatial data (Forsyth *et al.*, 2009), this demonstrates the importance of accurate and current spatial data for the Garden Route.

The study prioritised areas for invasive plant management in water-dependent ecosystems. As plants besides those identified as priorities can also be detrimental to aquatic ecosystems, the prioritisation of these species would be beneficial. The methods used in this study can be applied and the results used to improve IAP management in the Garden Route.

5.7 Conclusion

The Garden Route has a substantial IAP problem. The number of invasive tree species identified as priorities by published studies and their prevalence indicates the severity of the problem of IAPs and demonstrates how proper management must be implemented. It is therefore important to act now to combat the problem.

The results of this study demonstrate that SPOT-6 data are ineffective at separating invasive *Pinus*, *Eucalyptus* and *Acacia* species in the Garden Route. This is due to the lack of a red edge band and the spatial resolution being too coarse for the typical canopy size of these trees in the study area. However, SPOT-6 data were able to classify land cover and therefore can be used for this purpose.

WV-3 data were able to distinguish invasive tree species from one another and other tree species. This can be attributed to the finer spatial resolution (1.24 m) than SPOT-6 (6 m) and the addition of the red edge and yellow bands. Despite WV-3's capabilities, using the data in an area as large as the

Garden Route is limited due to the cost. For remote sensing to be a useful tool for invasive tree management, there needs to be a compromise between accuracy and cost. Remote sensing is not without its challenges but its practicalities for invasive tree management are steadily improving over time.

When used correctly, SCP software is a useful tool for conservation planning. It has many advantages, such as the time it takes to analyse large amounts of data, but for the results to be meaningful to management, appropriate spatial data must first be input. This study has demonstrated the importance of using appropriate spatial data to represent the criteria as this can influence the results. Since the purpose of the software is to support decision making, the results should be interpreted with discretion and used to compliment traditional approaches to invasive plant management.

The aim of this study was to determine which areas in the Garden Route should be prioritised for invasive tree species management. Although this was not achieved using remote sensing, priority areas were identified using a combination of existing spatial data and SCP software. This study has demonstrated the usefulness of SCP analysis, which is a tool yet to be fully utilised for IAP control.

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Appendices

Appendix 1. The GPS coordinates of the invasive tree species located in the Garden Route

Genus	Longitude	Latitude
Acacia	22.5346383	-33.99176554
Acacia	22.53604796	-33.99117635
Acacia	22.5363056	-33.99143632
Acacia	22.53884174	-33.98946216
Acacia	22.54635223	-33.98823373
Acacia	22.54752692	-33.98970232
Acacia	22.57823453	-33.99528727
Acacia	22.61111129	-33.9963224
Acacia	22.62963335	-33.98566374
Acacia	22.62282597	-33.98560003
Acacia	22.61776323	-33.98067746
Acacia	22.61732039	-33.98138264
Acacia	22.61720272	-33.98133498
Acacia	22.61901102	-33.97940572
Acacia	22.61528009	-33.97175729
Acacia	22.61378362	-33.9705214
Acacia	22.61344486	-33.96512966
Acacia	22.61698386	-33.96293393
Acacia	22.61734802	-33.96275581
Acacia	22.61832929	-33.96257507
Acacia	22.6183622	-33.96263608
Acacia	22.62122955	-33.96210575
Acacia	22.6222689	-33.96179859
Acacia	22.62234437	-33.9618676
Acacia	22.62297409	-33.96181957
Acacia	22.61633122	-33.96272252
Acacia	22.62126667	-33.94725124
Acacia	22.62159687	-33.94553765
Acacia	22.62307414	-33.94426837
Acacia	22.62466085	-33.94359773
Acacia	22.62795725	-33.94397104
Acacia	22.62915195	-33.94410904
Acacia	22.62988656	-33.94412755
Acacia	22.64834314	-33.93676325
Acacia	22.6487433	-33.93620324
Acacia	22.60511404	-33.95326263
Acacia	22.6039102	-33.95376053
Acacia	22.6039565	-33.95389815

Acacia	22.60150162	-33.95566022
Acacia	22.59791669	-33.95668884
Acacia	22.59390227	-33.95786551
Acacia	22.5911878	-33.95823013
Acacia	22.58979868	-33.95866958
Acacia	22.5861704	-33.95931836
Acacia	22.57640157	-33.96463784
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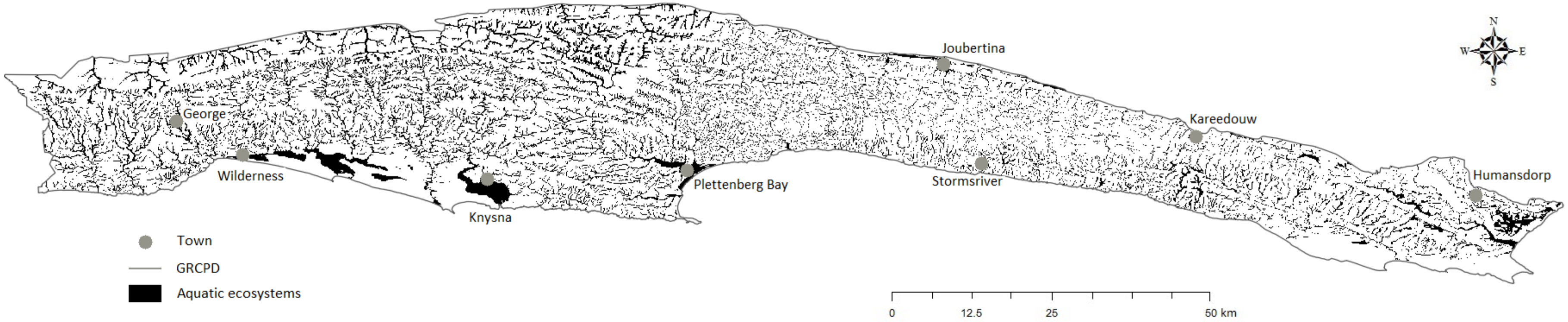
Pinus	23.31553436	-33.72752669
Pinus	23.32210091	-33.72728921
Pinus	23.19158445	-33.72717685

Appendix 2. The spectral categories used in ATCOR-2 to atmospherically correct the SPOT-6 and WV-3 data

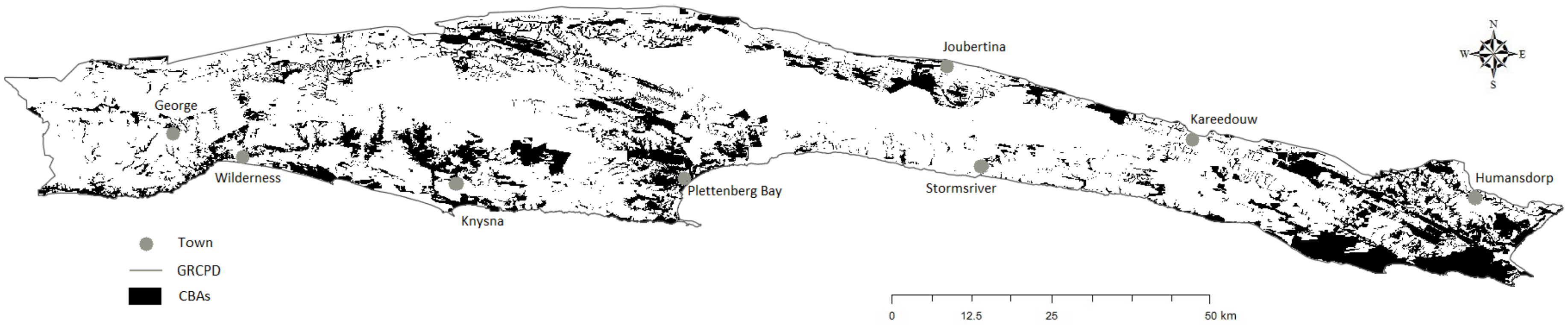
Land Cover	Spectra
Forest	Spruce (s4)
Gravel road	Bright soil (s4)
Water	Clear over bright sand (s4)

Appendix 3. The location of aquatic ecosystems in the Garden Route



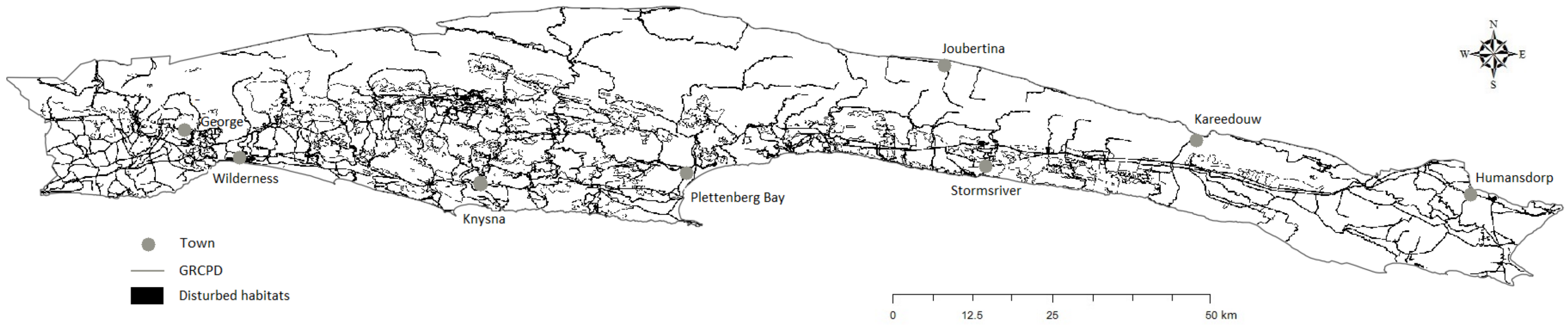
Appendix 3. Aquatic ecosystems (black) in the Garden Route.

Appendix 4. Critical Biodiversity Areas (CBAs) in the Garden Route



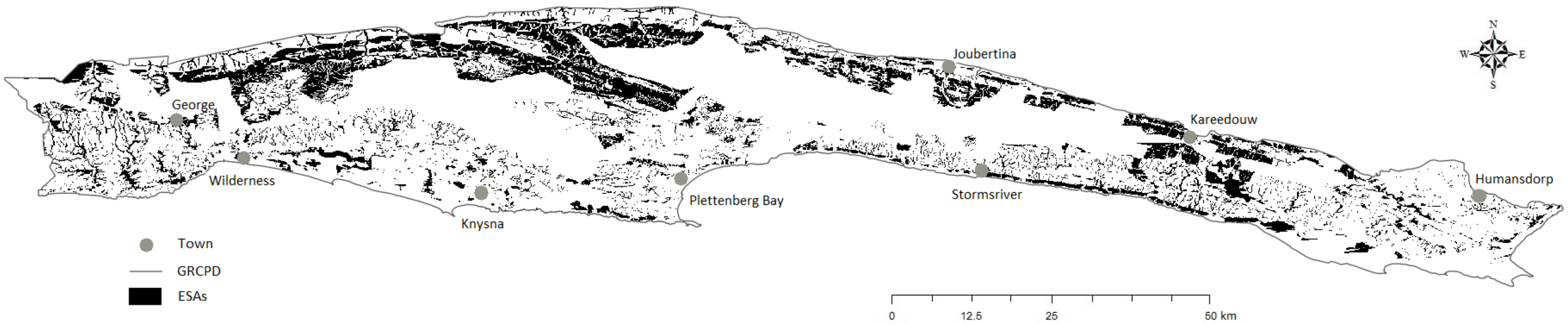
Appendix 4. CBAs (black) in the Garden Route.

Appendix 5. Disturbed areas in the Garden Route



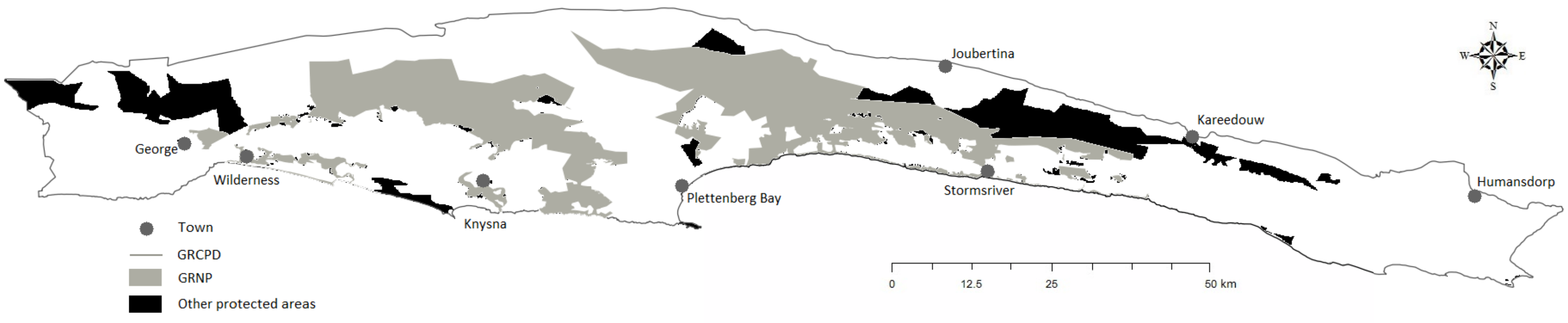
Appendix 5. Disturbed areas (black) in the Garden Route. These are areas within 100 m of a river, plantation boundary, road or path (Parendes & Jones, 2000; Alston & Richardson, 2006; McConnachie, Cowling, Van Wilgen, & Mcconnachie, 2012; Baard & Kraaij, 2014).

Appendix 6. Ecological Support Areas (ESAs) in the Garden Route



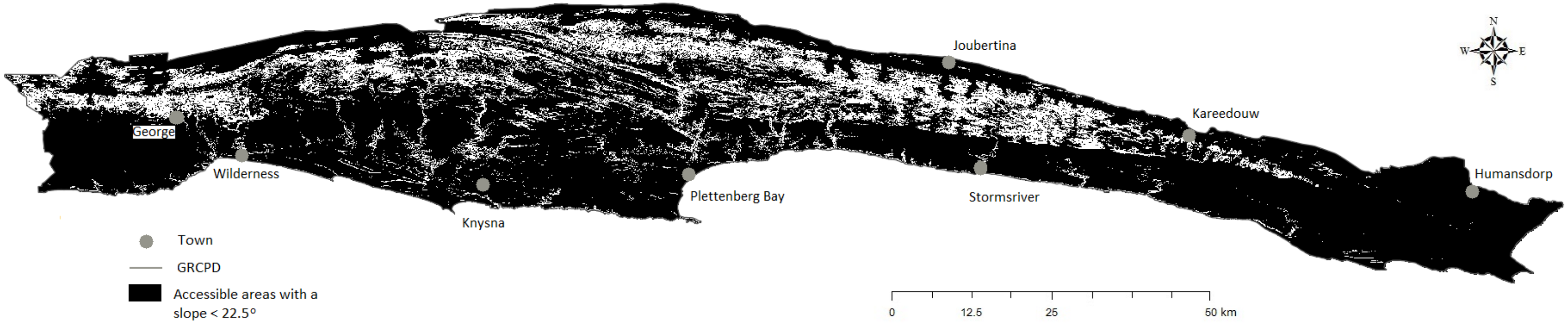
Appendix 6. ESAs (black) in the Garden Route.

Appendix 7. Protected areas in the Garden Route



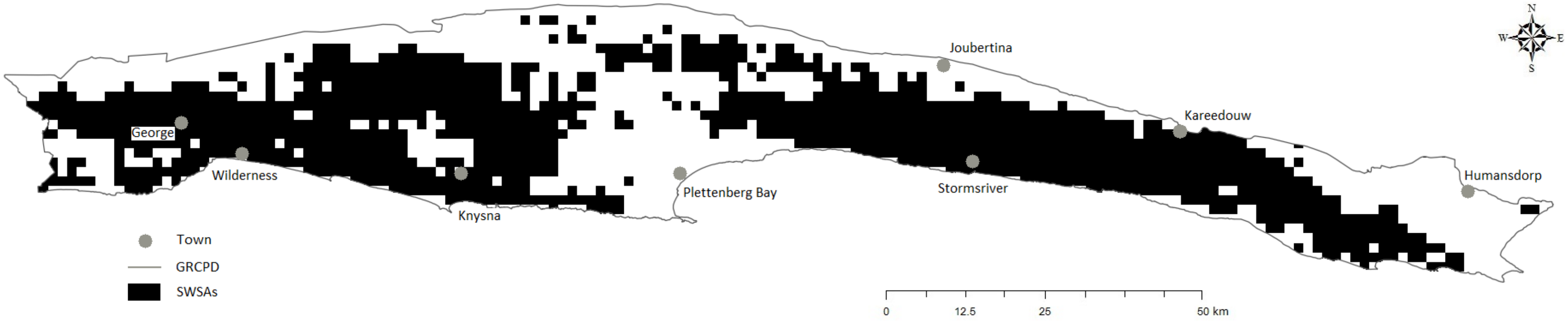
Appendix 7. Protected areas (black and grey shapes) in the Garden Route.

Appendix 8. Degrees of slope in the Garden Route



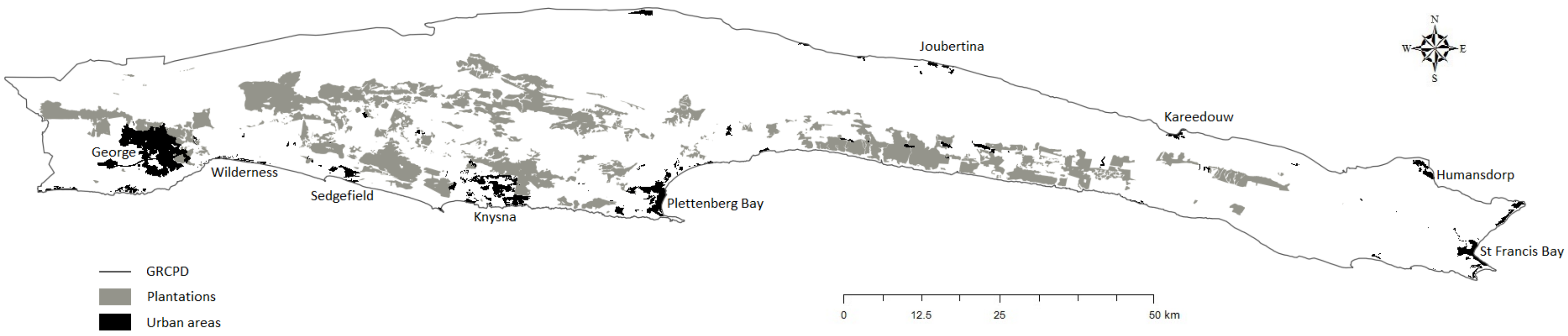
Appendix 8. Areas where the slope (<22.5°) are accessible to clear invasive tree species on foot in the Garden Route.

Appendix 9. Strategic Water Source Areas (SWSAs) in the Garden Route



Appendix 9. SWSAs in the Garden Route.

Appendix 10. Areas in the Garden Route excluded from conservation planning



Appendix 10. Areas excluded from conservation planning in the Garden Route (black and grey shapes).