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Environmental Engineering

Developing methods to assess the extent of naturalized slash pine populations and their habitats characteristics in South East Queensland, Australia

Blaise Dhont
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Supervision:
Prof. F. Golay (EPFL)
Dr. Y. Buckley (University of Queensland)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
THE UNIVERSITY OF QUEENSLAND

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Abstract

Slash pine is an exotic commercial species that is widely planted across South East Queensland's coastal region. Several studies have observed naturalized slash pine populations around plantations, although there have been minimal efforts to control reported ecological impacts. The aim of this project was to perform a pilot study within Bribie Island to develop methods for mapping slash pine wildings and defining their habitats characteristics; the final goal being to suggest management prioritization approaches. Cost and time effective large scale mapping requires a remote sensing based approach: this study applied the mixture tuned match filtering algorithm to a SPOT 5 image. SPOT data was retained since it was the most appropriate imagery available. The result of the MTMF classification was yet not satisfactory because of SPOT low spectral resolution. In order to determine habitats characteristics, a map of pine occurrence was however produced by stereoscopy. A logistic regression was then performed to predict pine occurrence as a function of distance to plantation, wind direction and ecosystem type. The three explanatory variables were obviously correlated to pine occurrence: slash pines were found within a 500 m buffer zone downwind to plantations and in a limited number of ecosystems. Distance was however the only significant variable for the model since pine presence was not adequately represented in the sample. In order to take the three variables into account, a qualitative approach based on a decision tree was performed to build a map of probability of pine occurrence. Risk maps were then derived combining the probabilities with the Biodiversity Status of the areas concerned. These maps provided the basis for a management prioritization strategy by defining the sensitive edges of the plantations where natural resource managers and the plantation company should concentrate their actions. Suggested management measures include the implementation of buffer zones (e.g. of slash pine clones or tall tree with dense foliage) to prevent seed dispersal, combined with remediation measures (i.e. slashing and burning). Concentrating management actions to high risk zones will maximise efficiency whilst limiting costs.

Résumé

Le pin d'Elliott est une espèce exotique largement cultivée le long de la côte du *South East Queensland*. Plusieurs études ont rapporté la présence de populations naturalisées autour des plantations, mais les efforts pour contrôler les impacts écologiques observés ont été jusque-là minimes. L'objectif de ce travail était de réaliser une étude pilote sur *Bribie Island* afin de développer des méthodes pour cartographier les pins naturalisés et définir les caractéristiques de leurs habitats; le but final étant de proposer une stratégie de gestion. Une approche basée sur les techniques de *remote sensing* a été employée pour la cartographie afin de limiter les coûts: le *mixture tuned match filtering algorithm* a été appliqué à une image SPOT 5, l'image disponible la plus appropriée. Les résultats obtenus n'étaient pas satisfaisants en raison de la faible résolution spectrale de SPOT 5. Afin de déterminer les caractéristiques des habitats, une carte d'occurrence des pins a également été construite par stéréoscopie. Une régression logistique a ensuite été effectuée pour prédire la présence de pins en fonction de la distance aux plantations, de la direction du vent et du type d'écosystèmes. Ces trois variables explicatives étaient clairement corrélées à la présence de pins car ces derniers étaient tous à moins de 500 m d'une plantation dans le sens du vent et dans un nombre limité de type d'écosystèmes. La distance fut cependant la seule variable significative retenue par le modèle puisque les observations « pin présent » n'était pas assez nombreuses dans l'échantillon. Afin de prendre les trois variables en compte, une approche qualitative basée sur un arbre de décision a été employée pour construire une carte de probabilité d'occurrence des pins. Des cartes de risque ont ensuite été produites en combinant les probabilités aux *Biodiversity Status* des zones concernées. Ces cartes ont servi de base à une stratégie de gestion en définissant les bordures des plantations sensibles où les actions de gestion doivent être concentrées. Les mesures de gestion proposées comprennent la mise en œuvre de zones tampons (composées p. ex. de clones de pins ou de grands arbres à feuillage dense) afin d'éviter la dispersion des graines, combinées avec des mesures de remédiation (abatage et brûlis). Concentrer les actions de gestion dans les zones à risque permet de maximiser leur efficacité tout en limitant les coûts.

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1 Introduction

1.1 Invasive alien species in Australia

Thousands of alien plant species have been introduced to Australia, mostly for cultivation and ornamental purposes, since European settlement more than 200 years ago (Parsons and Cuthbertson 1992, Randall 2007). Many of these species have successfully established and formed naturalized populations in the Australian environment, with the number of naturalized plant species estimated to be over 2000 (Humphries *et al*. 1991). The terms naturalized and invasive are used in this paper in compliance with Richardson *et al*. (2000) definitions. Naturalization starts when biotic and abiotic barriers to survival are surmounted and the plant reproduces in the wild, whereas invasion further requires the alien species to spread outside the areas of introduction.

Invasive alien plants are recognized to pose a serious threat to conservation of natural habitats and to have a tremendous impact on biodiversity (Cronk and Fuller 2001, Weber 2003). Around the world, they have also been shown to alter ecosystem functions (Le Maitre *et al*. 1996) and disturbance regimes, often with devastating consequences for native species (D'Antonio and Vitousek 1992). In 2010, designated the International Year of Biodiversity by the Convention on Biological Diversity (CBD), invasive alien species were recognized as a major driver of biodiversity loss worldwide and controlling invader populations was highlighted as a global priority (SCBD 2001). In Australia, Humphries *et al*. (1991) reported that invasive alien plants alter the structure, function, species composition and abundance of native communities. As a result, invasive plant populations are regarded as one of the principal causes of decline of native species in the country.

However, controlling multiple invader populations is a complex task. Natural resource managers are under pressure to take the most effective decisions with limited budgets. A key issue is to understand how the management of different invader populations in the landscape contributes to preserving biodiversity. Each invasive species occurs in certain habitats and bioregions - which are not always exhaustively known – and the threat differs from one ecosystem to another. The problem is thus different for each invader population and the level of risk depends on the impact and the proximity of the invasive species to the biodiversity asset.

1.2 Slash pine in Queensland

Slash pine (which includes *Pinus elliottii* var. *elliottii* and its hybrids with *Pinus caribaea*) is a fast growing conifer native to south-eastern regions of the USA. It was introduced to South East Queensland at the beginning of the last century for silviculture (Van Altena 1979). Slash pine is well adapted to the subtropical climate of Queensland and has become an important timber species and an excellent forestry investment (Barnett 2002). Parsons *et al*. (2006) report that slash pine has been extensively planted across the coastal regions of northern New South Wales and southern Queensland since the 1970’s, and that its popularity was reinforced when hybrids with Caribbean pine (*Pinus caribaea*) were developed to increase productivity in the late 1980’s. Based on their report, one can estimate that today slash pine represents more than 65% of the softwood resources in South East Queensland.

Slash pine is known to form naturalized populations in suitable habitat around plantations (McCarthy 1998). The first naturalized slash pine specimen was recorded in Queensland in 1978 (Queensland herbarium record), while naturalized populations were recorded only 10 years later in New South Wales (NSW herbarium record). However, slash pine was obviously present in the wild for a long time before it was first reported as so (Groves 1997).

Naturalized populations, also referred to as pine wildings, are recognized to form dense stands that shade out native species (Weber 2003) and certain countries such as South Africa consider it as a threat to national biodiversity assets (Henderson 2001). Although several studies warned of the invasiveness of slash pine in South East Queensland (Swarbrick 1983, Batianoff and Butler 2002), it is only listed as a pest by a few local councils in the coastal regions (Sunshine Coast Council 2011).

Presently, there have been minimal efforts to study and control the ecological impact for the majority of naturalized populations of slash pine throughout Queensland. Recorded population dynamics have not been extensively analysed and available documentation is limited. Consequently, there are extensive knowledge gaps about the invasiveness of slash pine wildings and their impacts. Coastal regions in Queensland are also home to several world-class national parks (e.g. Bribie Island National Park and Great Sandy National Park) and Ramsar[1] listed wetlands (e.g. Tin Can Bay and Moreton Bay). Considering the extent of current plantations, their proximity with major Australian biodiversity assets and the potential impacts of this invasive species, an assessment of the risk posed by slash pine is needed more than ever.

1.3 Objectives

It is generally more effective and cheaper to control a species if its spatial distribution is limited (Yokomizo *et al*. 2010). Currently, slash pine wildings have only been reported in habitats adjacent to softwood plantations (McCarthy 1998). Therefore, management measures would be much more cost effective and efficient to implement now, before naturalized pine populations possibly extend. This study aims to better map, document and understand the habitat preferences of slash pine naturalized populations. The driving questions are the following:

- What is the extent of naturalized slash pine populations in South East Queensland?
- What are the habitat preferences of naturalized slash pine populations?
- What are the habitats the most at risk and vulnerable to future slash pine invasion?

Given the time and budget constraints for this project, extensive field surveys and accurate mapping of current naturalized slash pine populations are not feasible. The goal is therefore to investigate whether a fast and cost effective method can give an overview of the problem and the management solutions that might be considered. Remote sensing has become a common tool to map large landscapes efficiently (Everitt *et al*. 1995, Lamb and Brown 2001) and provides a cost effective alternative to traditional ground surveys (Noujdina and Ustin 2008). The mapping process in this work will therefore be based on this technique.

A pilot study over Bribie Island was performed to assess to efficiency of the method. The choice of this area was motivated by the facts that Bribie Island is home to large slash pine plantations adjacent to a national park, is easily accessible for day trips from Brisbane, is well monitored (national park rangers, weather stations, etc.), is well documented (vegetation types map, fire management plan, etc.) and the spatial boundaries are clearly defined. Use of readily available data was given priority to be consistent with the objectives, although they might not be the optimal data. Once an efficient mapping method was developed, the habitats characteristics of invaded area were analysed. Finally, a risk map was produced and the application of the developed method to the other areas concerned by slash pine naturalization was discussed along with possible management measures.

[1] Ramsar convention is an intergovernmental treaty signed by 160 countries that provides a network for conservation and wise use of wetlands and their resources. It was adopted in 1971 in Iran.

2 Background

2.1 Slash pine characteristics

2.1.1 Nomenclature and origin

Two varieties of *P. elliottii* have been described: *P. elliottii* var. *elliottii* which is known as slash pine, and *P. elliottii* var. *densa* which is known as South Florida slash pine. Both subspecies are native to the south-eastern USA. Slash pine is the most frequently encountered variety and the only one that was commercially successful in Australia. It is therefore the only one considered in this report. Its native range includes the Atlantic Coastal Plain and the hills of South Georgia, but it has naturalized in other regions of the south-eastern USA where it has been introduced (Burns and Honkala 1990, Thieret 1993, McCarthy 1998, Barnett 2002).

2.1.2 Description

Slash pine is an evergreen conifer that varies from 18 to 30 m in height and averages about 0.6 m in diameter. It is characterized by a clear straight trunk and a relatively short ovoid crown with spreading and ascending limbs. The needles are 18-25 cm long and occur in bundles of 2 or 3 (Barnett 2002). Seeds are produced yearly with an average seed length of 6-7 mm and wing length of 20 mm (Thieret 1993), while a good crop is produced about every third year (Burns and Honkala 1990). The main dispersal mechanism of slash pine is by wind, some of the winged seeds may be carried as far as 75 m, although generally more than 90% fall within 48 meters of the parent tree (Burns and Honkala 1990, Barnett 2002).

2.1.3 Phenology

Slash pine phenology is mostly documented by Burns and Honkala (1990) and Barnett (2002). They report that slash pine is monoecious and wind pollinated. Flowering usually starts between 10 and 15 years of age but occasionally as early as 3 years old. The male strobili begin to grow in June, and develop for several weeks before entering a latent phase until midwinter. Pollen is released from late January through February. The female strobili start growing in late August until February or March. Cones are mature in September, approximately 20 months after being pollinated, and seeds naturally fall in October. However, dry weather hastens seed fall whereas wet conditions delay it (few seeds may be released until March). Seed viability is good and germination normally occurs from November to April. One has to notice that months have to be inversed for Australia's case since they are given for North Hemisphere conditions. Although it is hard to distinguish a hybrid from a non-hybrid, Dieters (pers. comm.) observed that some differences exist (e.g. hybrids don't stop growing in winter). However, influence on phenology is not well documented.

2.1.4 Natural occurrence

Burns and Honkala (1990) and Barnett (2002) also documented slash pine natural occurrence. Slash pine naturally grows in a warm humid climate with wet summers and drier falls and springs. It occurs throughout the flatwoods sites of North Florida and South Georgia, but it is also common along streams and edges of swamps and bays. Young seedlings are vulnerable to fire and ample soil moisture protects them. With improved wildfire protection, slash pine has spread to drier sites and colonized abandoned fields. The most encountered soil types in its natural range are spodosols, ultisols and entisols. The most suitable soils for slash pine are deep, well-aerated and provide ample quantities of moisture during the growing season, although it is adapted to a wide variety of conditions. Slash pine tolerates waterlogging, frost and salt wind. Slash pine can exist in a wide variety of plant communities, including coastal plant communities, coniferous forest, mixed forests and wetlands.

2.2 A global invasive species

Slash pine is an important timber species by virtue of its rapid growth rate and its production of valuable wood products. It was therefore widely planted in the USA and in other countries such as Australia, Brazil and South Africa (Richardson *et al*. 1994, Barnett 2002). Slash pine invasiveness was particularly studied in Brazil and South Africa where naturalized population were observed. In both circumstances, the negative impacts on biodiversity reported have caused it to be listed as an invasive plant.

2.2.1 Impact on invaded habitat

Weber (2003) mentions in his reference guide to environmental weeds that invasive slash pine populations in South Africa can establish dense stands that impede regeneration of native plants by shading them out. He also notes that over a period of time, invaded grasslands are transformed into species poor shrublands and forests. He finally reports that the most vulnerable habitats include grasslands, heathlands and scrubs, especially if they have been protected from fire for a long time. The Horus Institute (2005) informs that, in Brazilian steppe areas, the advancement of dense stands of naturalized slash pine populations has resulted in the replacement of the original vegetation as the latter is essentially heliophilous. Moreover, slash pine invasion is often accompanied by an increase in soil acidity and its litter’s slow decomposition hinders the germination of native species. Slash pine forests tend, therefore, to be strictly monospecific, preventing the recruitment of other vegetation. Horus Institute (2005) also warns that conversion of open ecosystems (fields, salt marshes, etc.) into closed ecosystems (forest) leads to soil exposure and consequent erosion and siltation of waterways that impacts on aquatic fauna.

2.2.2 Brazil

Slash pine is known as *Pinheiro Americano* in Brazil where it was introduced in 1948 along with other pine species (Horus Institute 2005). It is considered as an invasive exotic species of category 2 presenting a threat for all terrestrial habitats. A category 2 invader can be cultivated only under controlled circumstances (CONSEMA 2010).

Slash pine was found to be particularly easy to cultivate because of its rapid growth and intense reproduction in the south and south-east of the country. It was successfully planted in environments characteristic of savannah, as well as in the coastal plain (Horus Institute 2005). The southern grasslands, coastal sand dune vegetation, savannahs and many deforested areas are currently highly threatened by the invasion of slash pine and *Pinus taeda* (GISP 2005).

2.2.3 South Africa

Slash pine is considered as a category 2 invasive species in South Africa, which means it may be grown in demarcated areas providing that there is a permit and that measures are taken to prevent spread (Henderson 2001, Macdonald *et al*. 2003).

Moran *et al.* (2000) report that slash pine is one of the most important species for South African forestry. They also inform that large plantations are an important source of seeds and slash pine is now invasive and problematic. Invasion of conservation areas, displacement of native plant species and reduction of water run-off in catchment areas and water-flow in rivers are negative effects of naturalized pine population that have been observed. However, its importance for forestry industry excluded it from further consideration as a target for biological control. Other studies (Cowling *et al*. 1997, Henderson 2001, 2007, Wilgen *et al*. 2008) concluded that savannah, grassland and forest margins are biomes that are, or might be in the future, affected by slash pine, and high impacts on grazing potential and biodiversity are likely to occur.

2.3 Situation in South East Queensland

2.3.1 Plantation history

Slash pine was introduced to Queensland (Fig. 1) as a forestry species in the 1920's (Van Altena 1979). However, it only replaced hoop pine as the main planted softwood species in the 1970's, when, in a period of one decade, more than 24,000 ha were planted in South East Queensland (Parsons *et al*. 2006). In the 1980's slash pine plantings were replaced by Caribbean pine as land preparation technics provided better drainage (FPQ 2007). However, the development of hybrids combining the best characteristics of both species made slash pine (FPQ 2007) regain its position of most planted forestry species in South East Queensland in 1990's (Parsons *et al*. 2006).

Figure 1. Location of South East Queensland on Australian east coast.

The slash pine hybrid is now largely grown in the coastal regions of northern New South Wales and southern Queensland (McCarthy 1998). Parsons *et al.* (2006) estimate that approximately 65% of the softwood resources in South East Queensland is slash pine (against 20% for the Caribbean pine and 15% for the hoop pine). Caribbean pine is however the predominant species in North Queensland where slash pine only represent around 10% of the softwood plantations.

Forestry Plantation Queensland (FPQ) was founded in 2006 to manage state-owned softwood and hardwood plantations. FPQ informs that 73% of its plantation (i.e. 145,000 ha) was exotic pines in 2006. Non-hybrid slash pine composed 16% of that area, hybrids 40% and Caribbean 35% (the balance being a mixture of mostly radiata pine and loblolly pine) (FPQ 2007). The majority of exotic pine plantations are located in South East Queensland (Fig. 2) with the slash pine hybrid representing 90% of plantings since 2002 (Dieters 1996, Parsons *et al*. 2006, FPQ 2008). In South East Queensland, exotic pine plantations are found at Beerburrum, Fraser Coast (Tuan, Wongi and Toolara), Elliott River and Pechey (FPQ 2009, 2011).

2.3.2 An Australian invader

Slash pine is not recognized as a weed by either the federal government[2] or Queensland government[3] though its invasive characteristics have been noted (Batianoff and Butler 2002, Randall 2007). Naturalized populations adjacent to plantations have been mentioned often in the literature (Groves 1997, Lazarides *et al*. 1997, McCarthy 1998). Moreover, slash pine is declared as a threat to environmental assets by most local council regions along the central and southern Queensland coast such as Brisbane City Council (2007) and Sunshine Coast Council (2011). The latter warns it may naturalize in surrounding native forest and form dense stands that shade out other species and alter soil chemistry and structure. Thompson (1993) reported that slash pine is a problematic weed for coastal systems, open forests, woodlands and heath in several Sunshine Coast national parks (Pumicestone and Mt Tibrogargan National Parks). Swarbrick and Skarratt (1994) added to this list damp eucalypt,

[2] Australian Government, Weeds species, http://www.weeds.gov.au/cgi-bin/weedspeciesindex.pl?id=701, accessed 25/02/2011.
[3] Queensland Government, Weeds, http://www.dpi.qld.gov.au/4790_10168.htm, accessed 25/02/2011.

wallum heathlands, roadsides and wasteland, and reported slash pine occurrence in Glass House Mts National Park, the coastal region between Brisbane and Gympie, Mapleton Falls, Beerwah and Cooloola national parks as well as Sunshine coast. Brisbane City Council[4] mentions that soils ranging from deep cracking clays to sandy soils that are poor in nutrients are suitable to slash pine.

Swarbrick (1983) first highlighted the invasive impact of naturalized pine populations along the coastal regions of Queensland. He reported slash pine as a minor weed for non-irrigated improved pasture ecosystems and as a minor to medium weed for national parks. Twenty years later, (Batianoff and Butler 2002) reported significant slash pine invasion and impact, rating this species the 44th out of 200 invasive naturalized plants in South East Queensland. Presently, primary naturalized populations have reached sexual maturity (15 years) and secondary infestations are likely to occur. Dieters (pers. comm.) observed that slash pine hybrids are not sterile although they might produce less seeds than slash pine non hybrids as a result of their selection for wood productivity (and not cones productivity). He informs that the reason why hybrids were said to be sterile is that some of them (F1 type) were planted in blocks of clones having the same genotype, which resulted in poor seed production. Hybrids plantations therefore still release seeds in the adjacent habitats.

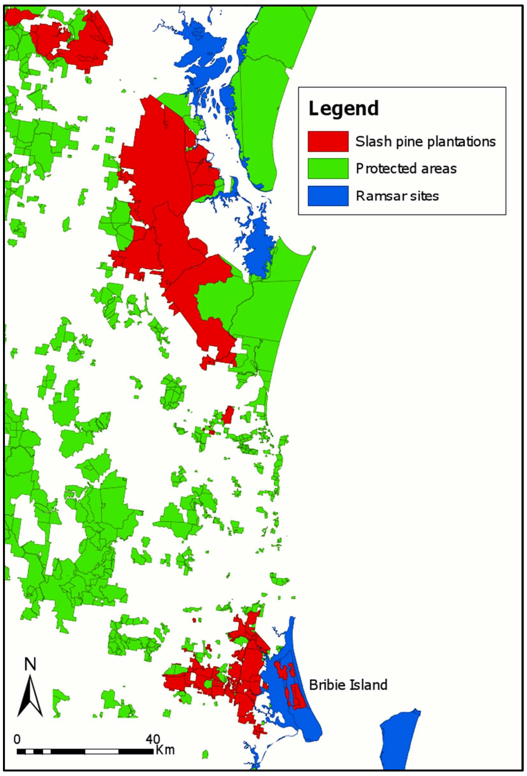


Figure 2. Slash pine plantations and the adjacent protected areas in South East Queensland.

2.4 Remote sensing of invasive species

2.4.1 Remote sensing of vegetation

Remote sensing refers to earth observation techniques based on devices that are not in physical contact with the ground surface, typically satellite and airborne sensors. The application of remote sensing to the study of vegetation systems and their functioning increased with the development of vegetation indices and their use with satellite imagery in the late 1970's. This technology today provides an important tool for studying vegetation and plant canopies. The main advantages of remote sensing include the fact that it is a cost effective, non-destructive, technology that can be applied exhaustively at large scales, which is of particular interest in ecological studies (Jones and Vaughan 2010).

The main remote sensing technique is based on the measurement of the electromagnetic radiations produced by target surfaces (e.g. a plant species) by a sensor. Any object on the earth's surface emits and reflects radiations. Two processes are involved, the first results from the fact that any object above a temperature of absolute zero emits a characteristic spectrum depending on its properties and its temperature. The second process is due to the interaction of solar radiation with the target surface. A part of the incident energy is absorbed by the object and the other part is reflected. This phenomenon is also wavelength dependent. Therefore, any object produces a unique spectrum of different wavelengths and intensities that can be used to identify it (Jones and Vaughan 2010).

[4] Brisbane City Council, Weeds, http://www.brisbane.qld.gov.au/environment-waste/weeds/, accessed 25/02/2011.

2.4.2 Soft classification methods

Image classification is a fundamental tool that is used to reduce the complexity of a remote sensed image to a limited number of classes (e.g. different vegetation types). Each pixel is classified based on its spectrum. Hard classification methods assume that the surface represented by each pixel contains one single class. This is rarely the case since most of the pixels overlap several classes (referred to as mixed pixel). The spectrum of a mixed pixel is the average response of each of the pure classes represented (the endmembers) weighted in proportion to the area occupied. Soft classification methods take that into account allowing partial membership of several classes. The typical output will be a set of images, each describing the proportion of a particular class within each pixel (Jones and Vaughan 2010).

Spectral mixture analysis (SMA) assumes the pixel spectrum as a linear combination of a limited number of spectrally different endmembers (Adams *et al*. 1986, Smith *et al*. 1990). However, this approach requires collecting spectra of all potential endmember components within the scene, which is often problematic (Noujdina and Ustin 2008). An improved alternative to SMA are partial unmixing methods, such as mixture tuned matched filtering (MTMF), which requires only the spectral endmember of the class of interest (e.g. an invasive plant) to be known (Boardman 1998). The fraction of the class of interest in each pixel is then computed. MTMF is therefore well adapted for invasive plant mapping since weeds are often mixed with other vegetation (which results in mixed pixel) and since the target species spectral signature is the only one needed. A major limitation of MTMF is that the invasive plant studied has to be somewhat spectrally different from the surrounding vegetation and be part of the canopy that is visible to the sensor (Adams *et al*. 1986).

2.4.3 MTMF for mapping invasive species

Cost effective, large scale and long term documentation and monitoring of invading species is a fundamental need for invasive plant management (Johnson 1999). The growing interest in hyperspectral detection of invasive plants over the last decade attests to the importance of remote sensing in this field (Everitt *et al*. 1995, Andrew and Ustin 2008). Several weed species were successfully identified from airborne hyperspectral images at high spatial resolution (Noujdina and Ustin 2008). The MTMF algorithm has been applied in some of these studies and provided meaningful results (Mundt *et al*. 2007).

Parker Williams and Hunt (2002, 2004) determined that MTMF processing methods were capable of detecting leafy spurge (*Euphorbia esula*) invasion with Producer's accuracies between 75% and 95% for canopy cover as low as 10%. Glenn *et al.* (2005) documented repeatability in discrimination of leafy spurge using MTMF and concluded that though discrimination can be made at 10% cover, the threshold is approximately 40% cover for repeatable and consistent detection. Pontius *et al.* (2005) implemented MTMF to delineate eastern hemlock (*Tsuga canadensis*) abundance and concluded the resulting percent hemlock basal area coverage correctly identified hemlock dominated pixels (> 40% basal area) with 83% accuracy.

Efficiency of MTMF algorithm applied to high spectral and spatial resolution imagery such as AVIRIS[5] is therefore demonstrated. However, hyperspectral data are not directly available for South East Queensland. The Department of Environment and Resource Management (DERM, Queensland government) commonly work with multispectral imagery. Among them is SPOT 5 (Satellite Pour l'Observation de la Terre) data which has a relatively good spatial resolution. Developing a method to apply MTMF algorithm to SPOT 5 imagery is therefore justified since they are readily accessible and do not need to be purchased by state government. However, the result is likely to be less accurate than what has been achieved with hyperspectral data.

[5] Airborne Visible InfraRed Imaging Spectrometer is an optical sensor developed by NASA.

3 Methods

3.1 Mapping naturalized populations

3.1.1 Study area

The study area for the pilot study is Bribie Island, centred at about 27°00’ S, 153°08’ E, which is located in the northern part of Moreton Bay in South East Queensland, Australia. The island is approximately 25 km long and 5 km wide, totalling 14,300 ha in size, with a maximum elevation of 10 m. Bribie Island is a popular holiday destination and a bridge links it to the mainland. The southern part of the island has been intensively urbanized as part of the Moreton Bay region. However, 85% of the island is protected and mostly constitutes the Bribie Island Recreation Area (which includes the 9660 ha of Bribie Island National Park). Natural habitat is mainly composed of an extensive system of wetlands.

Figure 3. Current slash pine plantations on Bribie Island (FPQ 2011).

James and Bulley (2004) report that the main vegetation communities on the island are *melaleuca* open forest, wetland and heath. Large areas of intertidal mudflats, saltmarshes, mangroves and seagrasses are found on the western edge. The eastern coast of the island is home to fire-sensitive beach ridge scrub and dune communities. The Regional Ecosystems[6] map for South East Queensland released by Queensland Herbarium (2010) in 2006 informs that 13 different Regional Ecosystems across 3 different Landzones are present on Bribie Island (Appendix A).

Slash pine was introduced to Bribie Island in the early 1960’s, and there are currently 3000 ha dedicated to plantations (Fig. 3). Plantations covered more than 4000 ha before their privatization in 2000. The only species currently planted are slash pine hybrids although plantations have included slash pine non-hybrids in the past. Bribie Island National Park rangers (Bulley, pers. comm.) consider slash pine as one of the main pests of the island. They estimate that 1200 ha of land, ranging out to 500 m from the plantations, are affected by naturalized slash pine population. Some of the well-established naturalized specimens are up to 50 years old. Older specimens are non-hybrids, and therefore both hybrids and non-hybrids are likely to be observed in the national park. Although slash pine is not a declared weed, measures are taken by the rangers to control pine. Regrowth is however often observed after slashing and burning. James and Bulley (2004) report climate in Bribie Island is subtropical with dry winters and most rain falling in summer. The driest months are in general June to September and the usual fire season is from around late September to March (peaking in November to December). Severe wildfires occurred in 1994, 2001-2002 and 2004. The latter

[6] Regional Ecosystems (REs) are vegetation communities associated with a particular combination of geology, land form and soil in a bioregion. A 3 number code (e.g. 12.3.6) designates each RE, the numbers indicate respectively the bioregion, the Landzone and the region. Landzone (Lz) refers to the soil type.

possibly killed 80% of the standing slash pines, but mainly in the plantation area. An extensive fire management plan is applied in Bribie Island and planned burns are mostly undertaken in July and August. Winds are generally from the south-east with northerly sea breezes in the afternoon during summer. Westerly or south-westerly winds predominate in winter.

3.1.2 Image acquisition and pre-processing

As mentioned in section 2.4.3, hyperspectral imagery is not readily available for South East Queensland. However, the Statewide Landcover and Trees Study (SLATS), which is part of DERM, work with multispectral images. SPOT products are the ones with the best spatial resolution. Queensland Herbarium provided a SPOT 5 multispectral image (Appendix B) acquired over the study area on the 2nd of July 2009 (the name of the product is s5hgre_53322698_20090702_bb2m6). The 4 spectral bands acquired are:

- green (0.50 – 0.59 µm),
- red (0.61 – 0.68 µm),
- near infrared (NIR; 0.78 – 0.89 µm),
- short wave infrared (SWIR; 1.58 – 1.75 µm).

The SWIR band yields 20 m pixels, which are then resampled to obtain a 10 m spatial resolution (the consequences of that transformation will be discussed in section 5). All the other bands yield directly 10 m pixels. The image was already pre-processed when it was furnished. It was orthorectified, georeferenced, and the at-sensor radiance L was transformed into top-of-atmosphere reflectance with consistent scalings applied. Reflectance ρ [W.m^{-2}.µm^{-1}.sr^{-1}] was calculated for each band as

$$\rho = \frac{L \cdot d^2 \cdot \pi}{E \cdot \cos(sz)}$$

where E [W.m^{-2}.µm^{-1}.sr^{-1}] is the incoming solar irradiance for that waveband, sz [sr] is the solar zenith angle, and d [AU] is the earth-sun distance factor for the date in question. These values (in the range [0-1]) were then scaled by multiplying by 10000 to give a 16-bit integer value. The values for E were obtained by convolving the filter functions for each SPOT band with the Kurucz values for the solar spectrum. These transformations were assumed to be sufficient considering the aim of the study (Phinn, pers. comm.). No further transformations where therefore applied before image processing.

3.1.3 Image processing and analysis

The method presented in this section is based on the work of Boardman *et al*. (1995), Parker William and Hunt (2002) and Mundt *et al*. (2007). All image processes were achieved using the Environment for Visualizing Images (ENVI) version 4.8 software (Research Systems, Boulder, CO), and the different steps (Fig. 4) were performed only on the portion of the image that covers Bribie Island to reduce data variability (the SPOT image covers a larger area that includes a part of the mainland and Moreton Island).

The MTMF algorithm requires the result of a Minimum Noise Fraction (MNF) transformation as input. MNF is a statistical data reduction technique based on a two-step Principal Component Analysis, to isolates noise and to reduce the volume of the data by transforming the original bands on orthogonal axes of variance (Green *et al*. 1988). This transformation is useful when applied to hyperspectral data as a large number of bands are available. It is however less relevant to reduce the dimensionality of the SPOT dataset since the image contains only four bands. All the bands of the MNF transformation output were therefore carried forward in the analysis.

The next step was to identify the endmember of slash pine. The four MNF transforms were used as input into a Pixel Purity Index (PPI) analysis which repeatedly projects data onto random unit vectors and notes the extreme pixels in each projection. The purest pixels are therefore rapidly identified (Boardman *et al*. 1995). The PPI analysis was performed on a pixel subset representing the slash pine plantations. Out of the four spatially different plantations, only the most south-eastern one has been considered as the others were slashed just before the SPOT image was taken. The plantation area is exclusively composed of slash pines (but some pixels might represent bare ground, shadows and isolated other plant species). However, only a part of the pixels can be considered as pure as the reflectance is influenced by many factors such as the orientation of the needles or the shadows. In this study, 10,000 iterations at a PPI threshold of 2.5 produced approximately 129,700 pixels considered as extreme in at least one projection. Of these, approximately 124,100 were discarded as they represented the lower 95% of the cumulative frequency distribution (PPI minimum threshold of 1000). The remaining “pure” pixels were then plotted in the N-Dimensional Visualizer (N-DV). The majority of the pixels were part of one of the three clusters that was observed. Comparing the spatial distribution on the SPOT image of each of these groups of pixels, it was established that the first cluster corresponded to bare ground, the second one to a cloud, and the last one (approximately 4,600 pixels) to slash pines. The average spectral signature of the pixels composing the dense centre of the slash pine cluster (approximately 1,100 pixels) was used as the endmember of interest in the MTMF (Fig. 5).

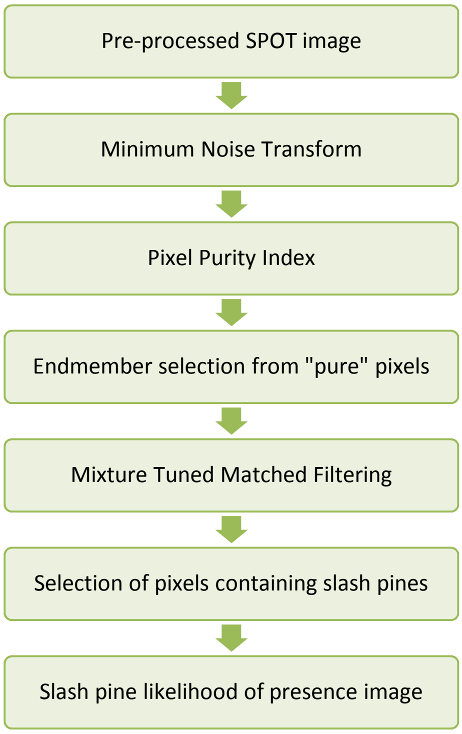
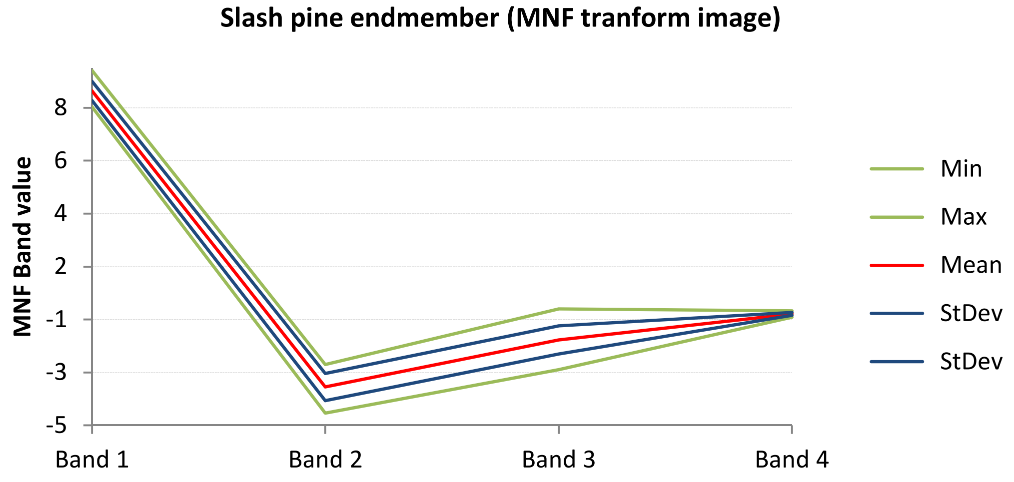


Figure 4. Flowchart of the image processing steps used for mapping slash pines from the SPOT 5 image using mixture tuned matched filtering (MTMF). This figure was modified from one by Parker William and Hunt (2002).

The MNF transformed image and the endmember extracted from the PPI results were used as input for the MTMF analysis. It outputs a matched filter (MF) score and an infeasibility value for each pixel. The MF scores is an estimate of the fraction of the pixel covered by slash pine and the infeasibility is a measure of how likely a pixel is to contain slash pines. It is however more appropriate in this study to interpret MF scores as the likelihood that a pixel contains slash pines since the complex interaction of electromagnetic radiation and forest results in a non-linear mixing of the different endmembers, what is against the initial assumption (Phinn, pers. comm.). A pixel can therefore be considered to contain slash pines if the MF score is greater than zero and if the infeasibility value is relatively low. Previous studies demonstrated that lower values of MF required lower values of infeasibility to be considered as not to contain the target species (Mundt *et al*. 2007). Scatter plots of MF scores versus infeasibility value were used in this study to evaluate to result of the MTMF. MF scores of zero or less were interpreted as non-pine and scores greater than 1 were interpreted as high percent target reflectance. The curve under which pixels contain slash pines was computed using the values in known occurrence of slash pine (i.e. plantations). The maximum infeasibility threshold was found to be 2 for MF scores greater than 0.55. Between 0 and 0.55, the maximum infeasibility threshold depends on the MF scores (Fig. 6). The pixels classified as containing slash pine (referred to as slash pine pixels) were exported into a Geographic Information System (GIS) for accuracy assessment.

Figure 5. Slash pine endmember for the MNF transformed image. The case of the SPOT image, computed using the same "pure" pixel as for the MNF case, is also presented because the bands are more meaningful. The MTMF classification was however performed on the MNF transformed data.



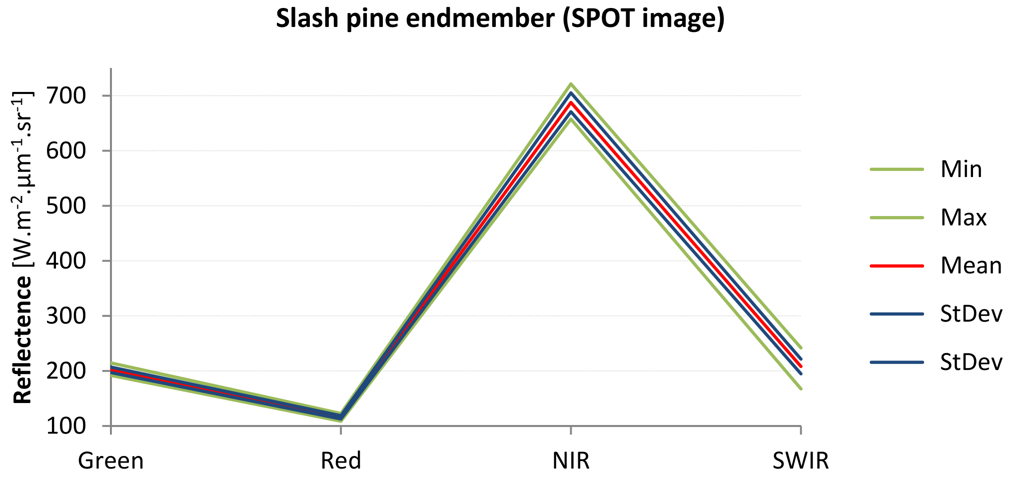
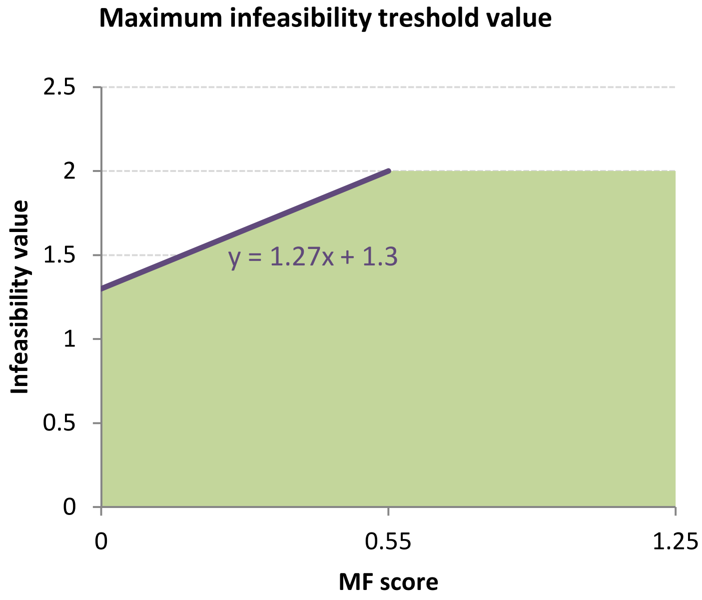


Figure 6. Maximum infeasibility threshold value. The area in green represents the domain of the scatter plot corresponding to slash pine (the points are not presented for visibility reasons).



3.1.4 Validation and accuracy assessment

MTMF classification accuracy was initially assessed by comparing the map produced with field knowledge acquired during the visit of the island and interviewing local rangers. MTMF classification results were also compared with the Regional Ecosystems map to estimate the reliability of the results for different vegetation types. This first step gave an idea of the quality of the map produced.

Then, during May 2011, ground data collection was performed for a finer accuracy assessment of MTMF classification method. It is assumed for this study that the use of 2011 field validation data is valid for imagery collected in 2009. Bribie Island National Park rangers did not proceed with any significant slash pine clearing during this period. 23 validation points located within areas mapped as slash pine by the MTMF classification (predicted positive) were surveyed. The main focus was to estimate commission error rather than omission errors as the latter were unlikely to occur since most of the vegetated areas of the island were detected as containing slash pine. Three factors determined the location of the validation points:

- the area must be accessible (only few tracks are passable in good weather conditions),
- all the Regional Ecosystems have to be represented in their relative proportions,
- different levels of MF scores have to be represented for each Regional Ecosystem.

It was planned to collect more ground data to adequately assess the MTMF classification. However, the first round of data was found sufficient to draw a conclusion (refer to section 4.1). Each point location was recorded using a Garmin eTrex Summit HC GPS (Global Positioning System) device. Slash pine canopy cover was measured with a convex spherical densitometer (Model A). Four measures were taken in the North, East, South and West directions and the average value was considered as the slash pine canopy cover at the validation point. The instructions provided by the manufacturer were applied (Appendix C). This method was retained for this study because it is fast, provides a direct measure of canopy coverage and is widely used in forestry. Visual estimations of canopy height, litter composition, vegetation composition and soil moisture were also noted for each validation point. Photographs of each site were taken.

Measuring DBH (Diameter at Breast Height) of slash pines present in each plot is an alternative simple method to estimate canopy cover. It was dismissed because it is not a direct measure of canopy cover (an additional error would be introduced) and it is too time consuming. A more appropriate method, which is used by SLATS, is to perform star transects of foliage projective cover estimation (Phinn, pers. comm.). Given the time and budget constraints and the characteristics of Bribie Island (dense vegetation and wetlands), such an extensive field work was however not feasible. The simple densitometer approach was therefore preferred. The accuracy assessment performed in that way was assumed to provide a sufficient estimation of MTMF approach reliability, at least at first.

10 ground control points (GCPs) were also collected using the same GPS receiver to estimate the georegistration error of the SPOT image. The GCPs were then transferred onto the SPOT image to estimate the horizontal positional errors. An obvious constant systematic error of approximately 206.5 m in the south-west direction was observed. It was corrected by performing a translation on all the GPS points. After the correction, no prevailing directional shift was detected; however, a maximum error of 1 pixel was observed. It means a positive classification may occur at distances up to 10 m from the predicted location in the SPOT image. To accommodate georegistration errors, Glenn *et al*. (2005) and Parker Williams and Hunt (2002) employed a buffering approach. In this study, the optimal buffer distance is assumed to be 10 m.

Error matrices are a common method to express the accuracy of a remote sensing classification (Congalton 2004) and it has already been used for MTMF results (Glenn *et al*. 2005). An error matrix of the validation points was therefore constructed according to Table 1. However, the ground data collection was designed to collect only points that were classified (to focus on commission error); true-negative and false-positive are therefore unlikely to occur. A bias might result from that. Moreover, this technique only considers pine presence/absence and does not give any information about MF scores accuracy. Parker Williams and Hunt (2002) used a different approach to take into account MF scores values. It consists in performing a regression of MF scores values against percent canopy cover of target species. To apply this approach in this study, the MF scores corresponding to each validation point were extracted. The computed accuracy will however be inferior or equal to the actual accuracy (Parker Williams and Hunt 2002) since positional error result in conservative bias of image assessments (Verbyla and Hammond 1995). Those two methods will also be performed separately for each type of Regional Ecosystems in order to assess whether accuracy depends on vegetation type.

Table 1. Accuracy assessment strategy with 10 m buffers of point data.

	Positive	Negative
True	Any classified pixel occurs within a radius of 10 m of a GPS reference positive sample.	No classified pixel occurs within a radius of 10 m of a GPS reference negative sample.
False	No classified pixel occurs within a radius of 10 m of a GPS reference positive sample.	Any classified pixel occurs within a radius of 10 m of a GPS reference negative sample.

Adapted from Glenn *et al*. (2005)

3.1.5 Stereoscopy mapping

Stereoscopy is a classic remote sensing method that is widely used by Queensland Herbarium to map vegetation cover (Butler, pers. comm.). The principle is to create an impression of depth by presenting separately, to the left and right eye of the operator, two images of the same scene taken from different points of view. This technique provides useful information that is not given by simple aerial photography by allowing the visualization of each feature's height. Stereoscopy was used to produce an additional map of slash pine wildings since MTMF classification results were not accurate enough to study naturalized slash pine habitat characteristics.

Queensland Herbarium provided a set of aerial photographs that were taken on the 11th of March 2002 over the southern part of Bribie Island and on the 27th of July 2003 over the northern part of the island. Stereoscopy mapping is labour intensive which limited the mappable extent of the study area. The study area was thus fixed to the vegetated area within 2 km from plantations since Bribie Island National Park rangers observed significant slash pine population only within 500 m from plantations (Bulley, pers. comm.). This statement from the rangers was verified during field trips. The area of interest was mainly covered by the 2003 aerial photographs.

Areas with known occurrences of slash pine (i.e. plantations and naturalized populations observed in the field) were used to identify features on stereoscopy images likely to be slash pine trees. Then, the zones with similar features were identified and mapped as containing pine. However, in forest areas, young or isolated pines are difficult to detect and a significant omission error was expected. Stereoscopy is more appropriate to detect dense populations in that type of vegetation. But since the final goal was to define habitat characteristics of the invaded areas, the accuracy of the map produced with stereoscopy was assumed to be acceptable. The habitat characteristics highlighted therefore correspond to relatively important slash pine populations. It is however reasonable to assume they represent the main ecosystems types threatened by slash pine invasion.

The map produced was not validated by groundtruthing since the zones of interest, in the northern part of the island, were not accessible with all tracks leading to these areas closed due to prolonged wet weather conditions. More importantly, differences between the current situation and the map were likely since the latter was based on 2003 photographs. For example, in the last decade, naturalized populations have been exposed to several intense wildfires and active removal, in addition to the natural spread of slash pines. A basic validation was still performed assessing the accuracy of the map with local rangers, and they confirmed that the map was relatively good although not very accurate in some areas (e.g. slightly infested zones). This was expected considering the aforementioned limitations.

3.2 Habitat characteristics

3.2.1 Explanatory variables

In order to determine naturalized slash pine habitat preferences, and to predict their occurrence, a model based on three explanatory variables was developed. The main environmental variables identified as likely to influence slash pine occurrence were: Regional Ecosystem type (*RE*), wind direction (*Wind*) and distance to plantations (*Distance*). *RE* is an important explanatory variable as it summarizes different key variables such as vegetation type, soil type and water table level. Regional Ecosystem map (Queensland Herbarium 2010) is directly available (as outlined in section 3.1.1) which avoids time consuming on-ground data collection. Wind direction and distance to plantations were identified as other key factors since slash pine seeds are wind dispersed (refer to section 2.1.3). Data were also available, with predominant wind direction known (refer to section 3.1.1) and the distance to the nearest plantation easily computed in GIS. Altitude and rainfall were assumed not to be relevant parameters on Bribie Island, particularly as the area is relatively small and flat. However, these two variables are likely to be important in other regions (e.g. on the mainland). Data preparation was performed using ArcMap version 10 (ESRI Inc., Redlands, CA).

3.2.2 Study area

Although the stereoscopy mapping was performed over the 2 km buffer zone around the plantations, the study area for this analysis was reduced to the 1 km buffer zone since slash pines were only mapped at sites very close to plantations (approximately within 250 m). Indeed, the size of the area containing pines has to be significant (i.e. large enough) compared to the study area to obtain meaningful results. Within that 1 km buffer zone, areas mapped as belonging to several Regional Ecosystems were dismissed to avoid introducing an error in the data (i.e. only the pure Regional Ecosystems were taken into account) since the only way to have considered them was to assume that the predominant Regional Ecosystem is the only one present. The Regional Ecosystem map provides the proportion of each Regional Ecosystem in each of these mixed RE areas but no information about their spatial distribution. Considering mixed RE as a class apart was not relevant since they are all different from one another; any information about ecosystem type would be lost.

To avoid sampling design problems, RE 12.3.1, RE 12.2.14 and RE 12.2.5 were dismissed because the concerned areas were too small (< 25 ha). Landzone 1 areas (i.e. RE 12.1.1, RE 12.1.2 and RE 12.1.3) were also dismissed as, apart the fact they represent small areas distant from plantations, they are not affected by pine invasion (refer to section 4.1). The final available study area represented approximately 4500 ha shared across 8 Regional Ecosystems. The study area included non-remanent type, which corresponds in this case to vegetated areas that are not part of plantations yet are not considered as a Regional Ecosystems because they are strongly influenced by human activity.

3.2.3 Sampling design

Twenty five points were randomly sampled in each Regional Ecosystem[7] to give the same weight to each Regional Ecosystem type. A small number of points were chosen to minimize spatial auto-correlation issues that occur when observations are correlated because of their spatial proximity (e.g. 2 spatially close observations are likely to be in the same Regional Ecosystem). For each of the randomly sampled points the following was recorded: slash pine presence, *RE*, *Wind* and *Distance*. As no wind model was available, each observation was classified as downwind (DWind) or upwind (UWind) to the plantations knowing that the main wind direction is from the south-east. The distance to plantations was computed[8] with respect to the former extent of the plantations (i.e. before privatization in 2000) rather than the current plantation licence area since the pine presence map was based on 2003 aerial photos. Out of the 200 sampled points, only 11 contained pine (approximately 5%). This is because the areas mapped as containing naturalized slash pine were relatively small compared to the study area.

However, the results obtained with that sample were not satisfactory (which is explained in section 4.2.1) and another one (referred to as sample 2) was collected to assess the influence of the sampling design. The same method was used except that the study area was extended to a 2 km buffer zone, the only pure Regional Ecosystems dismissed was RE 12.3.1 (which represents only 0.4 ha) and 50 random points were sampled in each Regional Ecosystems. The total number of observation was 650, out of which 26 were containing pine (approximately the same proportion as in sample 1). The two sampling methods were then analysed to assess habitat preferences and determine areas exposed to slash pine invasion.

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[7] The *Create Random Points* tool from the *Data Management* toolbox in ArcMap was used.
[8] The *Near* tool from the *Analysis* toolbox in ArcMap was used.

3.2.4 Analysis

The two samples were analysed using R version 2.12.1 (R Development Core Team, Vienna, Austria). Since the response variable was binary (pine presence/absence) and the explanatory variables were both continuous (*Distance*) and categorical (*RE* and *Wind*), a logistic regression and Likelihood Ratio tests were used to determine the influence of each variable on pine presence. This model has the advantage of not assuming a linear relationship between the response and the explanatory variables, nor a normally distribution of the error terms. The probability distribution is assumed to be binomial and the explanatory variables to be independent. A simple model that gives probability of pine occurrence as a function of *RE*, *Wind* and *Distance* was produced.

The result of the model was however not appropriate to generate a map of probability of occurrence because *Distance* was the only variable found to be significant (section 4.2.2). A different approach was therefore used to assess risk of invasion based on the results of the logistic regression and field knowledge, Bribie Island was classified into three levels of probability of pine occurrence (low, medium and high) depending on ecosystems type, wind direction and distance to plantations. Then, three levels of vulnerability were defined (low, medium and high) based on the biodiversity status. A risk map was finally produced by crossing the probability of pine occurrence with the vulnerability. Areas identified with both high probability of occurrence and high biodiversity values, i.e. high risk zone, might form the basis for prioritisation of management activities on Bribie Island.

In order to set the basis for large scale application of naturalized slash pine mapping and management, the characteristics of the zones transformed into plantations on the mainland were studied. The hard copy of current exotic pine plantations provided by FPQ (2011) was compared with the plantation licence area map to extract the zones planted, partially or not, with slash pine. Then, this map of current slash pine plantations was compared with the pre-clearing RE map provided by DERM. Under the assumption that the most suitable areas for pine growth were chosen to set plantations, the characteristics thus summarized provide an overview of habitats suitable for slash pine in south East Queensland. The characteristics of the areas adjacent to plantations, which are potentially threatened by pine invasion, were also extracted to assess their vulnerability.

4 Results

4.1 Image classification

The map produced by the MTMF classification is an estimation of the likelihood that a pixel contains slash pines in Bribie Island (Fig. 7). The south-eastern plantation is clearly visible, which indicates that serious omission errors are not likely to occur (the other plantations do not appear because slash pine was slashed before SPOT image was taken). This statement is reinforced by the fact that most of the island contains slash pines according to the map. However, the MTMF classification result presents an obvious strong commission error in certain areas. For example, pines are not likely to occur in the southern part of the island (far from plantations) (Bulley, pers. comm.) or in Landzone 1 areas (not suitable habitats) (Butler, pers. comm.), whereas the MTMF classification informs of the contrary. Also field observations confirmed that naturalized slash pines were localized around the plantations. It means that slash pine is confused with several types of vegetation, which was predictable since spectral resolution of the SPOT image is relatively coarse. The spectral signatures of several vegetated areas that were confused with dense slash pine population were compared with the slash pine endmember (Fig. 8). The spectral signatures were relatively similar which explains why the MTMF algorithm did not provide good discrimination for slash pine.

The result of the MTMF classification was compared with the Regional Ecosystems map (Fig. 7). As mentioned above, Landzone 1 areas are not likely to contain slash pine because of the high water table and saline conditions. The three RE of concern are:

- 12.1.1 *casuarina glauca* open forest on margins of marine clay plains,
- 12.1.2 saltpan vegetation including grassland and herbland on marine clay plains,
- 12.1.3 mangrove shrubland to low closed forest on marine clay plains and estuaries.

This is well illustrated by the case of RE 12.1.2 where 80% of the area does not contain pine (and the MF score of the remaining area is below 40%) according to the map. However, slash pines were predicted in most of RE 12.1.1 and RE 12.1.3 areas (respectively 80% and 60%) with a significant portion of dense slash pine populations (high MF scores). These ecosystems are known to be hostile to slash pine, it is therefore reasonable to assume that this result is due to a commission error.

Ecosystems which are predicted to be slightly invaded by slash pines, according to MTMF classification, are RE 12.2.7, RE 12.2.12 and RE 12.2.14 (Fig. 9). If each Regional Ecosystem is assumed to be homogenous in its spectral signature, it might be reasonable to consider that the result of the MTMF classification is reliable for these three Regional Ecosystems. However, they are all shrubland or woodland which means the slash pines detected in these areas might in fact be isolated trees of other species that occur naturally.

Regional Ecosystems detected as strongly invaded by slash pines are very likely to present a strong commission error since slash pine does not occur in large dense stands. For example, RE 12.2.5 was predicted to be mainly covered by slash pine (75%) with the highest proportion of dense slash pine population (15% of the area with MF scores greater than 80%) although it is far from plantations. Confusion between slash pine and other kinds of trees is likely to be the origin of those results. RE 12.2.5 is the most extreme case, but similar comment can be made for RE 12.2.14, RE 12.2.7, RE 12.2.9 and RE 12.3.4 since they have the same MF scores distribution pattern.

The case of RE 12.3.5 and RE 12.3.6 is different because, while they are predicted to be mainly covered by slash pine, the MF scores are low (below 40%). Previous studies showed that accuracy is reduced for areas with low canopy cover (Glenn *et al*. 2005). The MTMF classification result could be thus considered more reliable in those cases, especially as the

Regional Ecosystems concerned are next to plantations. This observation has to be taken with caution as there can be confusion between tree species, as already highlighted. The accuracy assessment will give a better estimation of reliability of the map.

Figure 7. Likelihood of slash pine presence in Bribie Island (MTMF classification output).

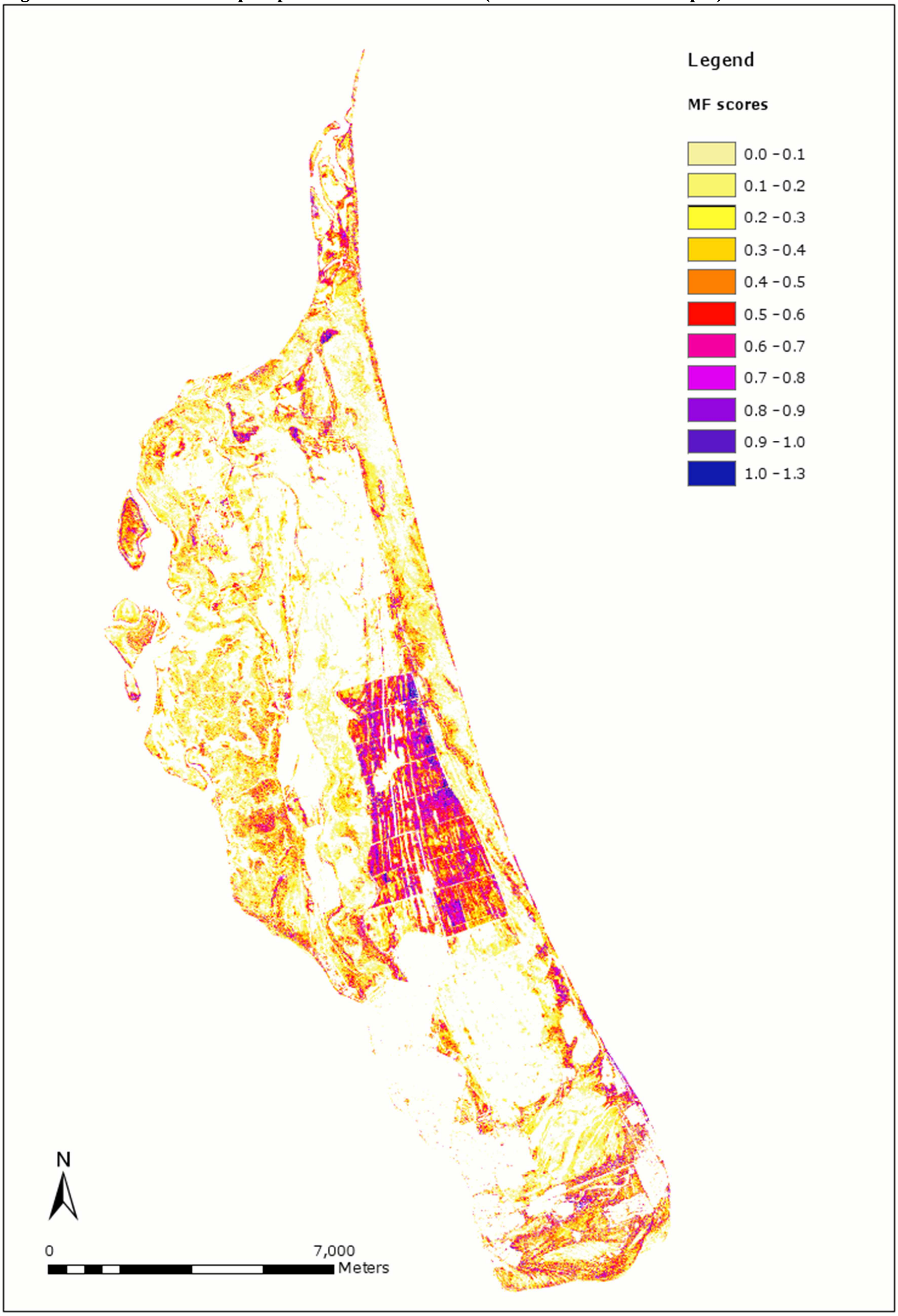


Figure 8. Spectral signatures of areas with high MF score (> 60%) confused with slash pine. The legend gives the Regional Ecosystem corresponding to each area.

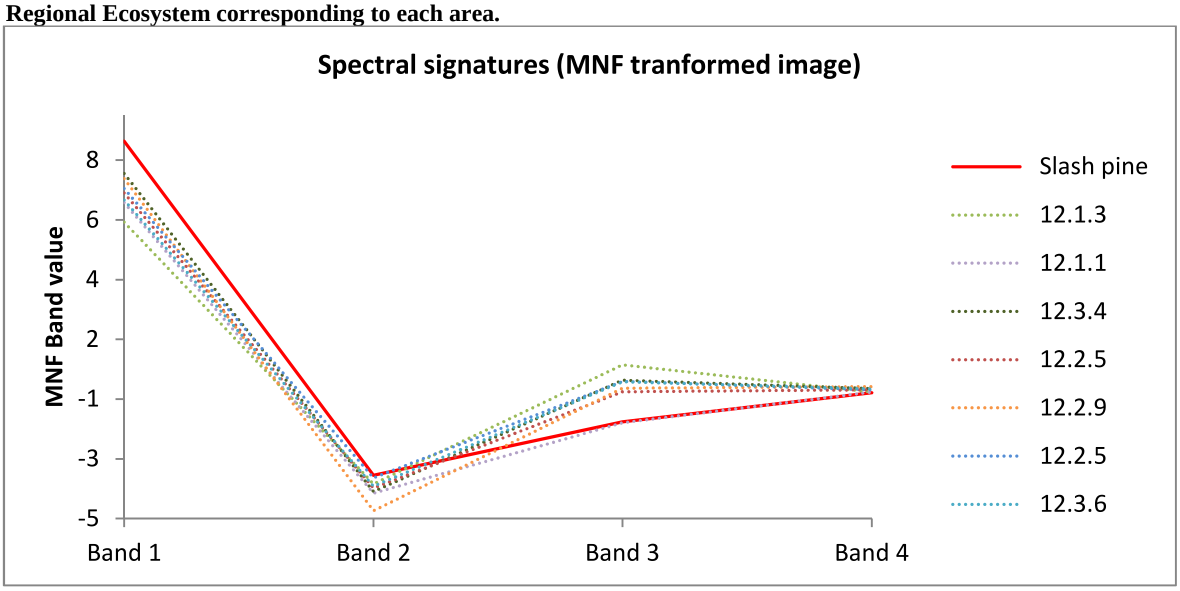
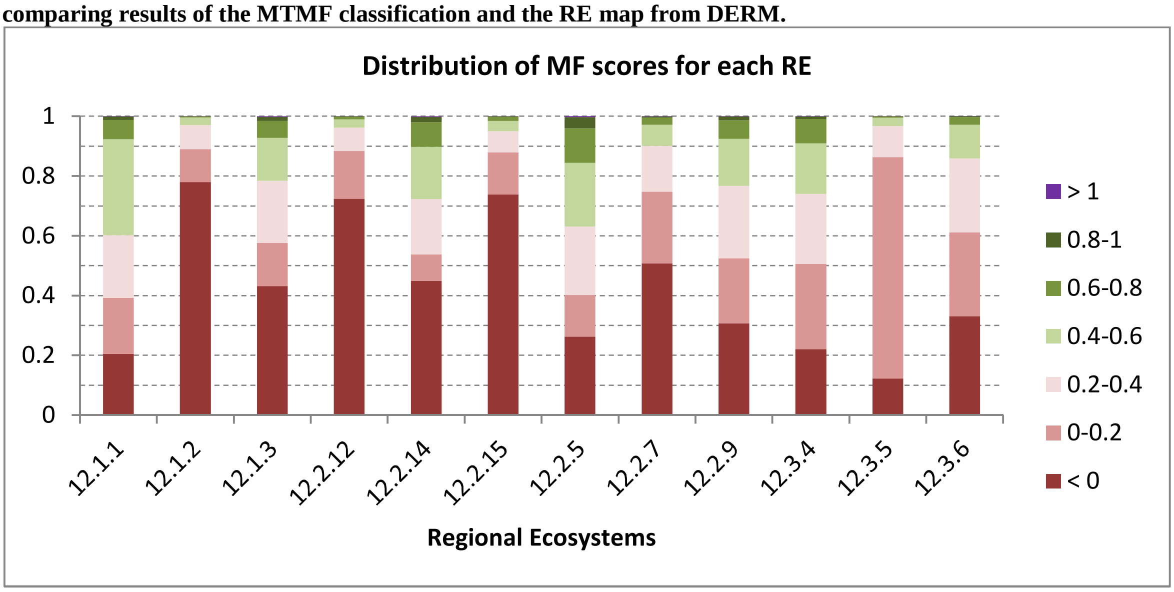


Figure 9. Distribution of MF scores for the main Regional Ecosystems of Bribie Island. Only the pure ecosystems were considered (some area are classified as belonging to several RE at the same time). This figure was obtained comparing results of the MTMF classification and the RE map from DERM.



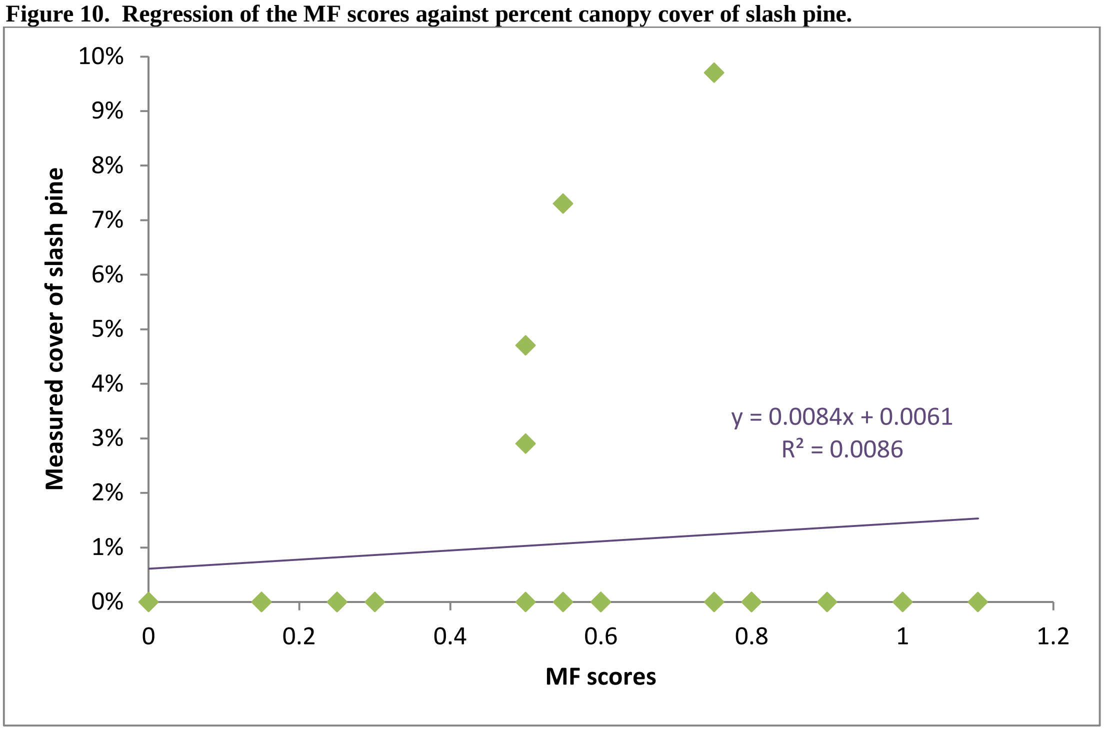
Results of the accuracy assessment (Table 2) for slash pine presence demonstrated an overall accuracy of 17%. All the 23 sites surveyed were classified as pine containing (true) whereas only 4 of them actually contained pine (true-positive). This explains the Producer's accuracy of 100% for pine presence (all the pine presence were detected) and of 0% for pine absence (none of the pine absence were detected). If observations had been collected randomly across Bribie Island instead of within the areas detected as pine containing, the result would have been slightly different. The presence of some not classified observations would slightly lower the Producer's accuracy for pine presence (because the omission error is low) and increase Producer's accuracy for pine absence (because some false-negatives would have been surveyed, although most of the "false" observations are false-positives because of the strong commission error).

The four true positive observations were located in RE 12.3.6, RE 12.2.5 and RE 12.3.5. However, their measured slash pine canopy covers are very low (< 10%) whereas the corresponding MF scores are high (> 50%). Figure 8 presents the scatter plot of slash pine cover versus MF scores. It shows that even when slash pines are detected, the MF score is not accurate. The regression equation has a slope very close to zero whereas the slope should be relatively close to 1 when good results are obtained. Moreover, the R^2 value is very low. No further tests were needed to conclude that the results of the MTMF classification are not reliable. In order to increase the map accuracy, a minimum threshold value for MF score (e.g. 40%) could have been set. But this is not sufficient in this case as many of the false-negatives (sites confused with pine) have high MF scores.

Table 2. Error matrix (in number of validation samples) and accuracies (in percent).

		Reference			
		Present	Absent	Row totals	User's accuracy
Classified	Present	4	19	23	17%
	Absent	0	0	0	100%
Column totals		4	19	23	
Producer's accuracy		100%	0%		
Overall accuracy		17%			

Figure 10. Regression of the MF scores against percent canopy cover of slash pine.



4.2 Habitat characteristics

4.2.1 Variables

Distance was compared to *Wind* and *RE* for the two samples (Fig. 11 and 12) to verify if the variables were independent. In both cases, the upwind sites are on average further from plantations than downwind sites. This is because the plantations are closer to the shore in the downwind direction (i.e. in the north-eastern direction) which results in a buffer zone that is less than 1 km. However, if a 500 m buffer zone is considered (Fig. 13), the same effect is still observed, yet in a smaller proportion. This is because at the border between the upwind and downwind sites, the sites distant from plantations are classified as upwind whereas the closest ones are already classified as downwind. *Wind* and *Distance* are therefore not independent although the correlation is relatively low. *Distance* is also slightly correlated with *RE*. This is because the different Regional Ecosystems are not uniformly distributed across Bribie Island and because they are not equally represented in size. The correlation is stronger for sample 2 since the latter includes the small Regional Ecosystems that are likely to be represented in only few sites (i.e. either close or distant to plantations). Non-remanent zones are strongly correlated with *Distance* because they represent areas adjacent to plantation that are not part of the national park. The Pearson's Chi-squared test between *RE* and *Wind* indicates these two variables are also not independent. This might be explained by the fact that the main wind direction influences the spatial distribution of the different vegetation type (i.e. sites that are exposed to wind do not have the same ecosystems than sites protected from wind). The three variables cannot therefore be considered as independent. This observation will be taken into account during the interpretation of the logistic regression results.

Distance discriminates pine presence well, especially in sample 2 case (Fig. 14). All pine presences were very close to plantations (approximately within 250 m) whereas the majority of pine absence sites were further away (this effect increases in sample 2 case since there are more sites distant from plantations because of the wider buffer zone). The wind direction appeared also to be a key factor: all the pine present observations were downwind of the plantations for both samples. Concerning Regional Ecosystems, slash pine was detected in a limited number of vegetation types in each sample (Table 3). Non-remanent is the main type where slash pines are encountered. This was predictable since these areas are adjacent to plantations and not managed by the rangers. Regional Ecosystems belonging to Landzone 3 are the second most common vegetation types that contain slash pines. However, one has to be careful since the latter are the predominant ecosystem downwind of plantations (Appendix A). Therefore, Landzone 2 ecosystems cannot necessarily be considered as non threatened by pine invasion. One may notice that, in this pilot study, Regional Ecosystems don't add any additional information compared to Landzones, although their level of complexity is higher. According to the parsimony principle, Landzones will thus be considered for building the risk map instead of Regional Ecosystems. The latter might however be relevent in other regions such as on the mainland.

Figure 11. Boxplots of wind direction and Regional Ecosystems against distance to plantations for sample 1.

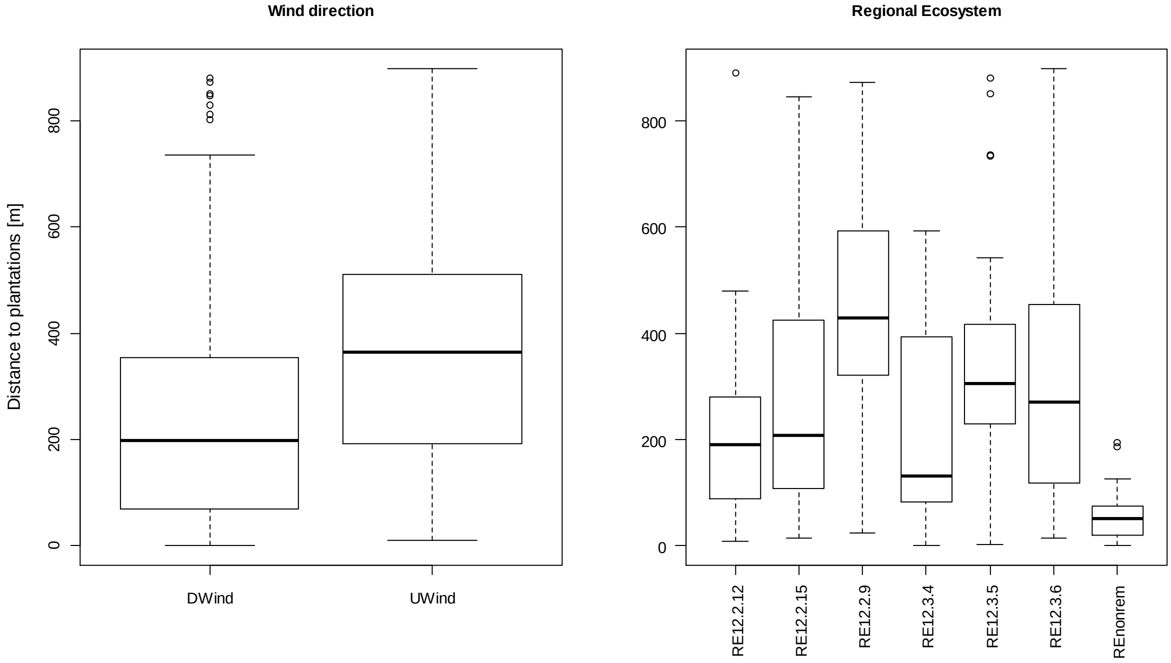


Figure 12. Boxplots of wind direction and Regional Ecosystems against distance to plantations for sample 2.

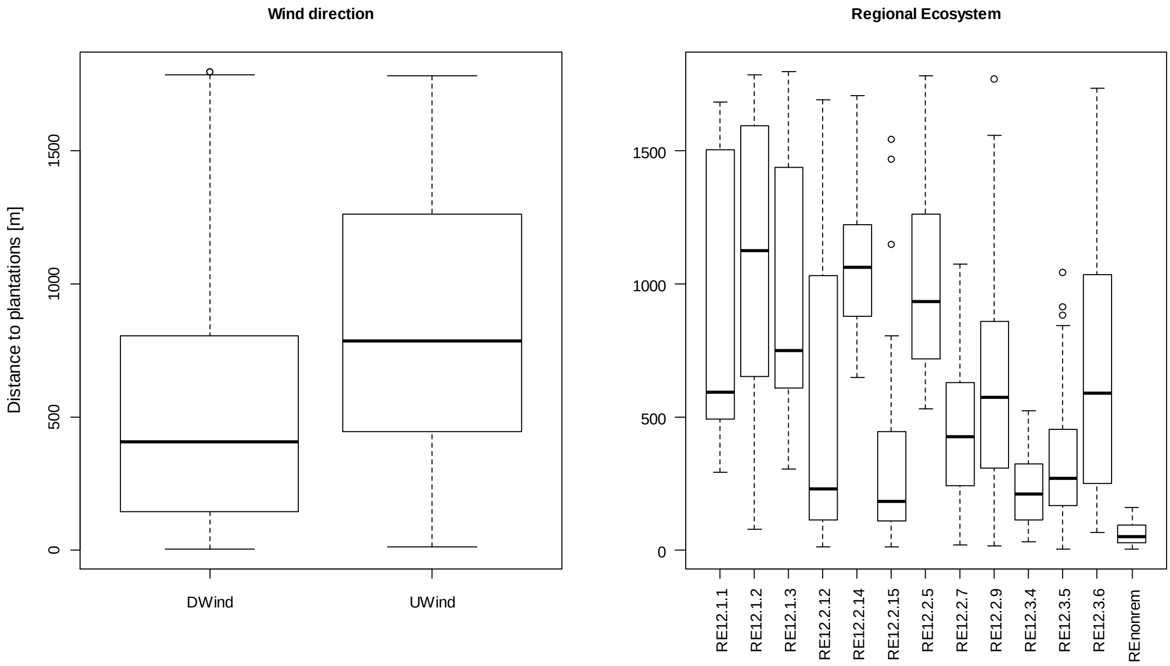


Figure 13. Boxplot of distance to plantations against wind direction in the case of 500 randomly sampled points in a 500 m buffer zone around plantations.

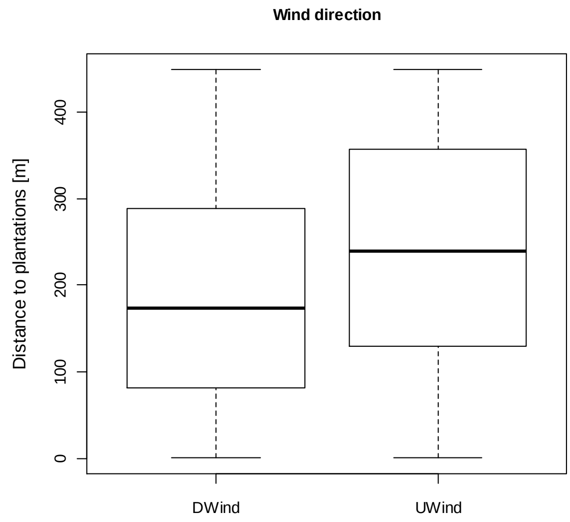
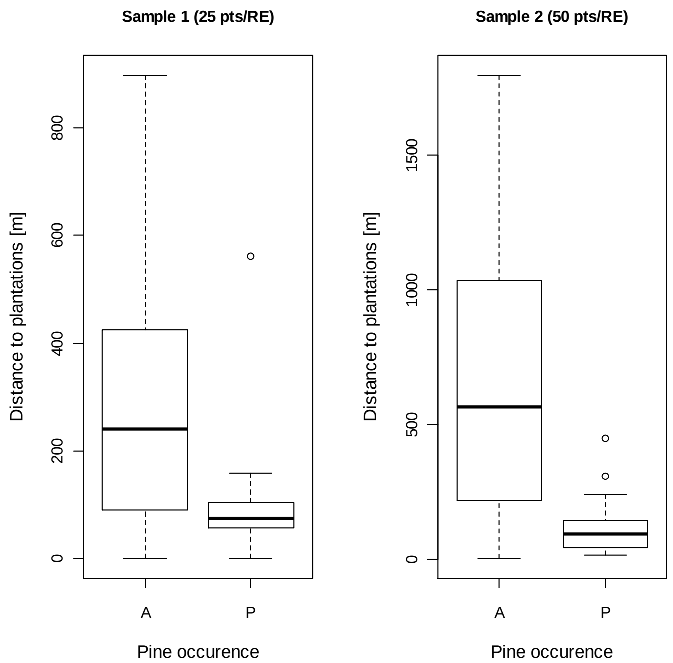


Table 3. Pine presence/absence against Regional Ecosystems types for the sample 1 and sample 2.

RE	12.1.1	12.1.2	12.1.3	12.2.12	12.2.14	12.2.15	12.2.5	12.2.7	12.2.9	12.3.4	12.3.5	12.3.6	non-rem
sample 1 (25 pts/RE)													
A	-	-	-	25	-	25	-	25	25	24	25	21	19
P	-	-	-	0	-	0	-	0	0	1	0	4	6
sample 2 (50 pts/RE)													
A	50	49	50	50	50	50	50	50	50	48	48	47	32
P	0	1	0	0	0	0	0	0	0	2	2	3	18

Figure 14. Boxplots of pine occurrence against distance to plantations for sample 1 and sample 2.



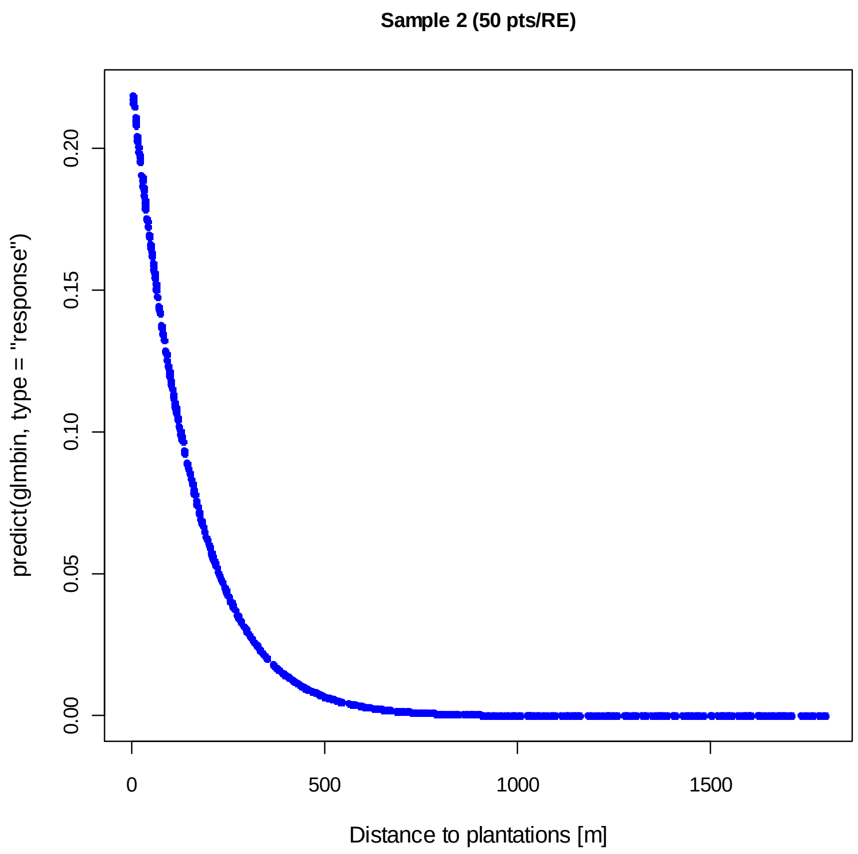
4.2.2 Logistic regression

The logistic regression was performed with a binomial model with no interaction between the explanatory variables using R software:

```
glm(pine ~ wind + re + dis, family=binomial)
```

No variable was found to be significant with sample 1 whereas *Distance* was significant in the case of sample 2 (P-value = 0.0422) (results presented in Appendix D). This is because the latter had more pine presence in the absolute. Sample 2 is thus the only one considered in the following. The probability of occurrence was computed as a function of distance (Fig. 15). It shows that pines are not likely to occur further than 500 m of plantations. This observation confirms the ranger's statement (Bulley, pers. comm.). The fact that the variables are not independent can explain why *RE* and *Wind* are not significant: the latter share the variance of *Distance* between them. But there is another important fact that explains the results of the model: slash pines were detected with stereoscopy in a few sites only. Therefore, even if the characteristics of those sites are homogenous, i.e. very close to plantations in the downwind direction and belonging to Landzone 3 or RE non-remanent, a lot of similar sites do not contain pine. These characteristics were used to build a probability of occurrence map that does not depend only on distance to plantations.

Figure 15. Probability of pine occurrence as a function of distance to plantations computed from a logistic regression for sample 2. The area under the curve indicates the probability of pine occurrence within a given buffer zone.



4.2.3 Risk map

A qualitative approach based on a decision tree was performed to assess the probability of pine occurrence (Fig. 16). Three parameters determined the latter: wind direction, distance to plantation and Landzone type. *RE* was replaced by *Landzone* variable; as explained in section 4.2.1, *Landzone* was a sufficient level of segregation. The four values that can be taken are Lz 1, Lz 2, Lz 3 and non-remanent. The values of these three parameters were chosen based on the results of the logistic regression as well as field knowledge.

Wind direction was demonstrated to be an important factor that influences seed transportation and the upwind/downwind classification was kept. The second ramification is a function of distance to plantations. In the downwind direction, the threshold values were 250 m (high probability) and 500 m (medium probability) since the model showed that most of slash pines occurred within 250 m of plantations although some might be found as far as 500 m. However, slash pine seeds are unlikely to be transported as far in the upwind direction; therefore the first threshold value was set to 150 m instead. Finally, according to the Landzone type, different probabilities of occurrence were assigned (high, medium or low) based on the result of the regression.

A vulnerability map was also produced using biodiversity status of the Regional Ecosystems. “Endangered”, “Of Concern” and “Not of Concern” areas were respectively classified as high, medium and low vulnerability. A risk map (Fig. 17) was finally built crossing the probability of occurrence map with the vulnerability map, as summarized in Table 4.

Figure 16. Decision tree that gives a qualitative probability of slash pine occurrence as a function of wind direction, distance to plantation and Regional Ecosystems type.

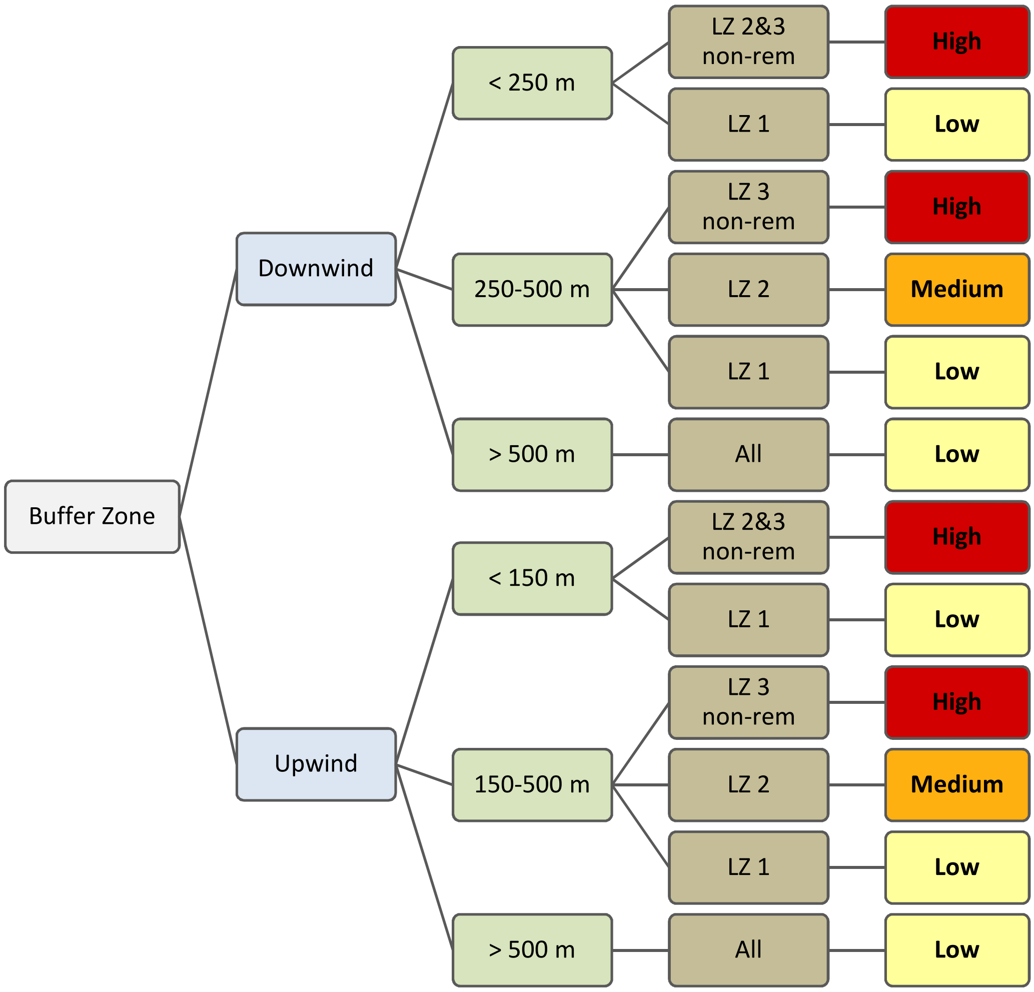
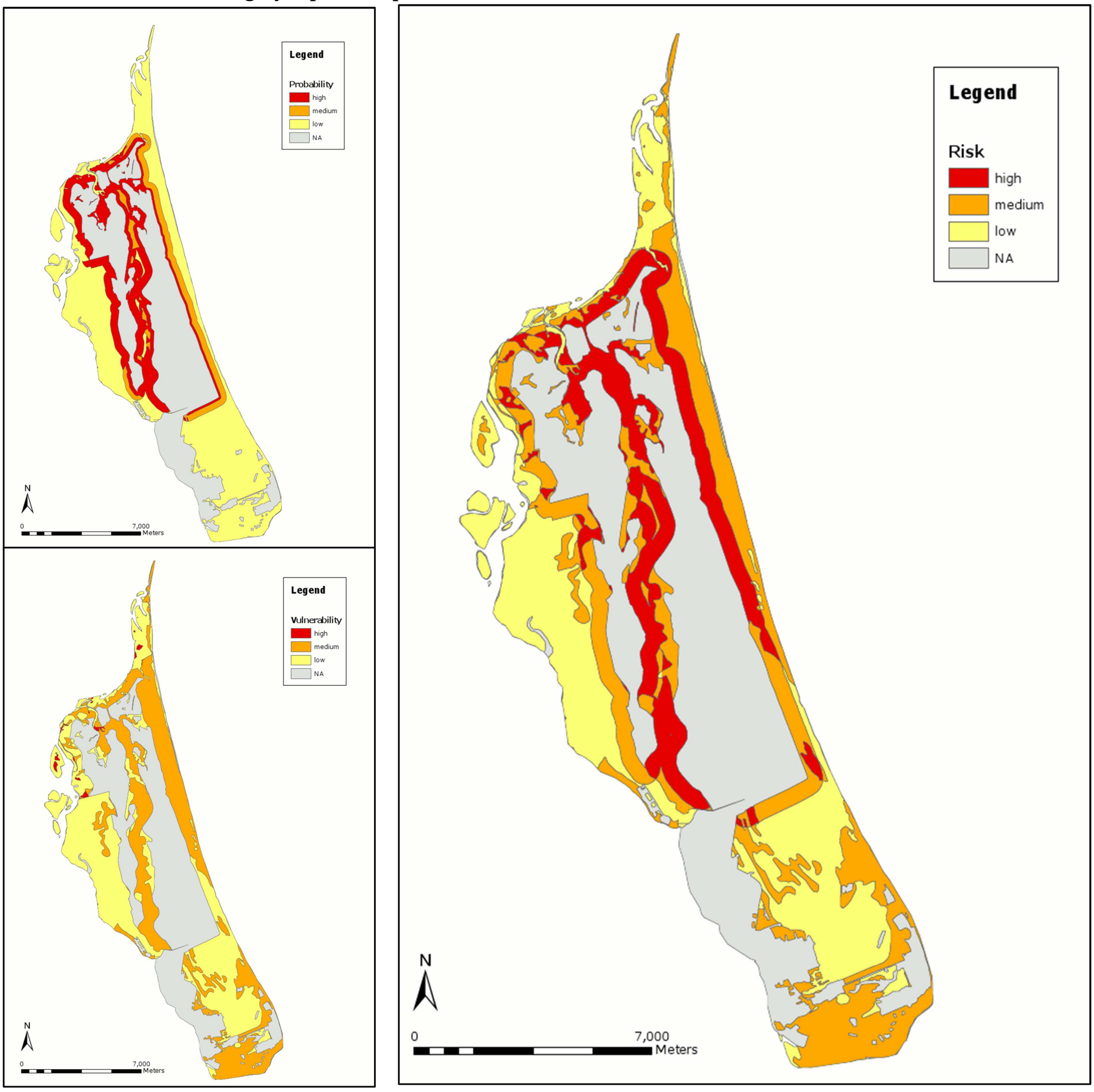


Table 4. Classification of Bribie Island into three levels of risk as a function of probability of pine occurrence and vulnerability.

Probability	**High**	Medium	High	High
	Medium	Medium	High	High
	Low	Low	Medium	Medium
		Low	**Medium**	**High**
		Vulnerability		

Figure 17. Probability of pine occurrence, vulnerability of the Regional Ecosystems and risk of slash pine invasion in Bribie Island. The area in grey represents plantations and urbanized zones.



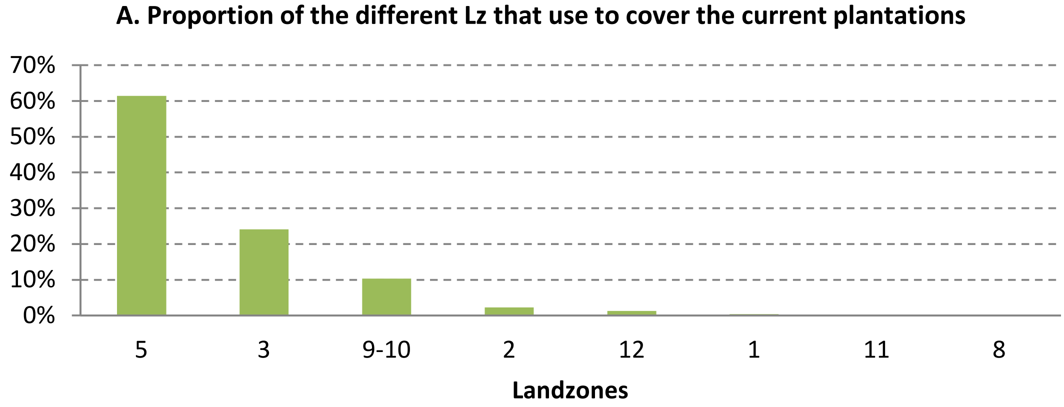
4.2.4 Mainland plantations

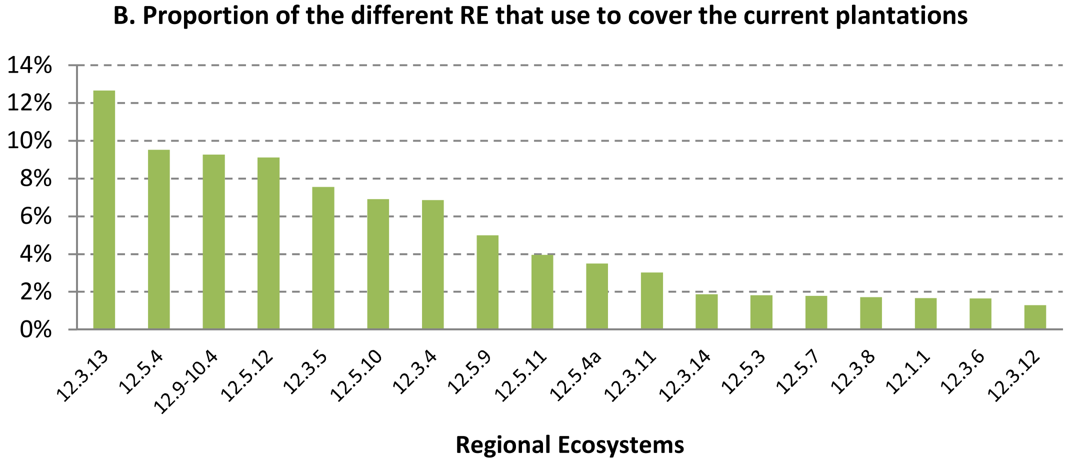
An overview of the slash pine issue on the mainland, where the largest plantations are located, is presented in this section. The slash pine plantation map for South East Queensland was first compared with the pre-clearing Regional Ecosystems map in order to extract the characteristics of the lands that were turned into plantations (Fig. 18; Appendix E). Three Landzones types use to cover more than 90% of the actual plantation area (Fig. 18A): Lz 5 (60%), Lz 3 (20%) and Lz 9-10 (10%). Their descriptions are given in Appendix F.

The environmental characteristics of the lands chosen to set plantations are likely to be similar to ones of the habitats suitable to slash pine naturalization. The different Regional Ecosystems highlighted (Fig. 18B) give therefore an overview of the ecosystems that might be invaded on the mainland. One may note that slash pine habitats preferences on mainland are relatively different from the ones on Bribie Island (different Regional Ecosystems and Landzones types are concerned). This introduces the issue of the choice of Bribie Island for a pilot study, discussed in section 5.2.

The Regional Ecosystems present within the 500 m buffer zone around the slash pine plantations were then extracted: it came that approximately 2,600 ha of land are classified as "Endangered" and 12,000 ha as "Of Concern" according to their Biodiversity Status. It represents more than 14,600 ha of natural habitats to protect from invasive species and other threats. These statistics highlight the fact that sensitive ecosystems are adjacent to plantations, and thus exposed to slash pine invasion. The issue posed by slash pine in South East Queensland is thus confirmed.

Figure 18. Landzones types (A) and Regional Ecosystems types (B) turned into plantations in South East Queensland (based on the pre-clearing RE map from DERM). The REs presented represent 90% of the total area.





5 Discussion

5.1 Mapping

The results of MTMF classification applied to Bribie Island's SPOT 5 image were not satisfactory and did not fulfil expectations: many tree species were confused with slash pines. Obviously, this can be attributed to the image low spectral resolution since slash pine endmember was not sufficiently spectrally distinct from the native vegetation. Another factor could be that the spectral signature of slash pine itself may not be sufficiently different from surrounding species. In previous studies that used MTMF algorithm to map invasive species, the target plant (e.g. leafy spurge) had distinctive spectral features (Parker Williams and Hunt 2002). Future studies aiming at mapping slash pine using partial unmixing approaches will therefore have to answer two questions: is slash pine sufficiently spectrally different and is the imagery spectral resolution sufficiently high? This may be reworded as: is slash pine endmember sufficiently unique?

However, attempting to map slash pine wildings with SPOT 5 imagery was relevant. Hyperspectral data are not directly available for South East Queensland and are expensive to obtain. Queensland Herbarium currently works with SPOT images and it would have been very useful to find a sufficiently accurate mapping technique using multispectral data. Moreover, no study to date has demonstrated that SPOT imagery was not appropriate to map invasive pines. One may notice that, although it was not the goal, plantations and different types of vegetation were successfully mapped from the SPOT 5 image. This observation might provide a basis for future studies with such an objective.

It is important to note that when the 20 m pixels of the SWIR band are sub-sampled into 10 m pixels, the radiometry of each pixel and its relation with the corresponding area on the ground are destroyed. Consequently, it is not possible to unmix these pixels correctly (e.g. with the MTMF algorithm) as the fundamental assumption of linear area-based mixing no longer applies (Phinn, pers. comm.). The Green, Red and NIR bands are not concerned since they are not sub-sampled. However, the SWIR band was taken into account in the image processing steps and the result is certainly negatively affected. This highlights some limitations of the MTMF algorithm: all the bands must have the same spatial resolution and sub-sampled bands are not appropriate.

Another issue rises from the fundamental assumption that each pixel spectrum is a linear mixing of the different endmembers it contains. This assumption is often verified in the case of flat surfaces such as water and grass, but it is not the case on Bribie Island where most of the sites of interest are covered with forest. Trees are vertical objects and the interaction of the electromagnetic radiations within the canopy and understory results in a non-linear mixing of the endmembers (Phinn, pers. comm.). This non-linear mixing introduces an error in the MTMF output. The locations of previous studies that applied MTMF algorithm were characteristic of grassland (Parker Williams and Hunt 2002, Glenn *et al*. 2005), which is a more appropriate vegetation type for this technique. This is the reason why the MF scores were interpreted as a likelihood of pine occurrence rather than canopy coverage (refer to section 3.1.4). However, despite the error introduced, the orders of magnitude of MF scores computed were consistent.

Stereoscopy is not the most appropriate method to map slash pine in the case of South East Queensland since the areas of interest are mostly covered with relatively dense forest and naturalized pine population are often scattered. Moreover, it is a time consuming technique and the potential areas on mainland currently invaded, or at the risk of invasion, are relatively large (what is not the case at Bribie Island scale). Future studies will need to focus on automated remote sensing techniques such as MTMF algorithm to minimise inputs in map construction. Also, this study highlights the fact that the appropriate imagery has to be used when applying the algorithm, as relevant spatial and spectral resolutions are needed to detect a study species, yet these images must be at the same time affordable. These suggestions introduce the issue of slash pine not considered as a weed by Queensland State Government, which manages South East Queensland national parks. There are no legislative requirements for slash pine naturalized populations to be managed, and therefore no funds are allocated for that purpose. Local councils are more likely to be interested in assessing naturalized slash pine extent, but the cost must comply with their limited budgets.

5.2 Habitat characteristics

If the aim is prioritizing slash pine management, rather than mapping slash pine wildings, reliable results might be obtained from the naturalized slash pine habitats preferences that can be defined by an extensive field study. The method presented in this study can be a basis for such an approach. The habitat characteristics combined with other variables (e.g. distance to plantation and wind direction) can be used to predict pine occurrence. Risk maps can then be derived by including the biodiversity value of the different ecosystems concerned. The fact that data, such as Regional Ecosystems map, is directly available through DERM is a major advantage. The sampling design have however to take several points and limitations into consideration; the Bribie Island pilot study showed that naturalized slash pines might be spatially localized (i.e. concentrated is small areas) and that the sampling has to be planned in consequences to obtain relevant results.

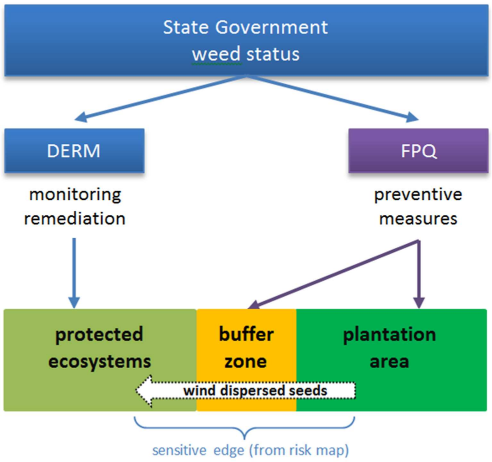
The Regional Ecosystem map is relatively coarse and is not very accurate in some cases according to its description. The inclusion of the RE map in future studies depends on the level of accuracy needed to make informed management recommendations. In the case of Bribie Island, where naturalized slash pines are relatively localized because of the management performed, more accurate data would be useful to produce better estimation of habitats characteristics. But on another hand, the area is relatively small and high accuracy results are not particularly relevant for the rangers who manage slash pine invasions. The advantage of using the Regional Ecosystem map is that an extrapolation can then be performed since South East Queensland is already entirely mapped. If more accurate environmental variables are measured for each observation, more accurate habitats characteristics might be defined, but no probability of occurrence maps can be produced. The feasibility of such an approach will depend on the field knowledge of the rangers who actually manage invasive pines (i.e. if they know which areas correspond to the habitats profiles defined).

Biodiversity status of habitats surrounding plantations on the mainland supports the necessity to assess the impact of naturalized slash pine populations. This research showed that Bribie Island is not the best area to perform a pilot study on this type of weed. The island does not have enough representatives of the environmental characteristics that can be found on the mainland. Future pilot studies must be designed so that all the different Regional Ecosystems and explanatory variables are taken into account. Even if better results were obtained for Bribie Island, the extrapolation of the model to the mainland would have been difficult. A logistic regression is however an appropriate modelling approach to predict pine occurrence, with main explanatory variables being wind direction, distance to plantations and ecosystems types at the regional scale. The fact that naturalized populations might be relatively localized has to be taken into account when defining the future sampling and analysis methods to be used.

5.3 Management measures

The two major parties involved in slash pine wildings management in South East Queensland are DERM (QWPS) and softwood plantations owner (FPQ). The former depends on state government and its management actions generally consist in remediating invaded zones. The main techniques currently used for pine wildings are a combination of slashing and burning. However, DERM's future management actions are limited by the lack of state weed declaration for slash pine. The second actor is a private company that has to apply the rules enacted by the state government. These rules depend also on slash pine status and the company's actions are in general preventive. Therefore, the two main actors depend on state government and on slash pine status. Their actions must be coordinated to be the most efficient, and their interaction spatially corresponds to the borders of the plantations.

Figure 19. Slash pine management strategy.



Slash pine plantations cannot be banned because of their economic value. However, slash pine status can be raised to the level of class 3 weed, as it is the case in other countries, to provide a legal basis to management actions. Currently, natural resource managers' resources are limited and no measures can be imposed to FPQ because of the status issue. The first goal of the management actions must be to limit the seed dispersal of slash pine outside the plantations, and especially into sensitive ecosystems. This is the most appropriate preventive measure considering the current situation. One approach is to plant sterile trees; however, sterile hybrids haven't been developed yet (refer to section 2.3.2) and this solution is not the most relevant at the moment. An alternative is to focus on the borders of the plantation and implement measures to contain seeds to within the plantations. Impermeable structures are not feasible, but the amount of seeds dispersed in the surrounding area can be sufficiently decreased to lower their impacts if such a risk measure was undertaken.

One possible way to contain seeds in the plantation area is to set a buffer zone (e.g. 50 m) at the edge of the plantations with clones planted so that the amount of seeds produced by the pines close to the edge (i.e. the pines susceptible to released seeds in areas adjacent to plantations) is strongly limited (refer to section 2.3.2). The seeds produced in the central part of the plantations are not likely to be transported further than the buffer zone. Other approaches based on buffer zones are conceivable. For example, a buffer zone composed of vegetation requiring fire regime can be set around the plantations and regularly burned to kill the young pine seedlings. The latter are very sensitive to fire and light burning can therefore be performed. Such an approach allows performing the slashing and burning actions in the buffer zone, which is more easily manageable, rather than in the ecosystems adjacent to plantations. A possible third measure is to plant a hedge of tall trees with dense foliage around plantations so that they act like a net that retain wind dispersed seeds. The advantage of this last measure is that there is minimal costs and future maintenance needed. The different measures presented can be adapted from case to case and combined.

These different approaches are however difficult to apply extensively. This is why habitat characteristics of invaded area must be studied prior to implementing any measures. The risk map that can be derived from habitats characteristics allows prioritizing the area to manage, and therefore limiting the management actions to the sensitive borders. The cost of management measures is thus reduced while maintaining their efficiencies. The sensitive borders are likely to be the ones downwind to plantations and close to protected ecosystems that are suitable to slash pine naturalization. Other preventive actions can be undertaken such has performing slash pine cutting when the wind is favourable and impede fallen seeds during the process to be blow away (the ground is particularly exposed to wind when the plantation have been chopped down). Knowing high risk zone is also useful to help the resource managers to monitor and remediate the invaded habitats. This is true for the current situation, but also under the hypothesis that the preventive measures suggested are undertaken. As previously mentioned, a certain amount of seeds is likely to be dispersed in the area adjacent to plantations although preventive actions are implemented. Therefore, complementary action may be necessary outside of the plantations to contain slash pine invasion. The risk maps would enable defining areas that require constant monitoring and the ecosystems that have to be preserved in priority. The total area in contact with plantations is relatively important (the 500 m buffer zone around slash pine plantations in South East Queensland represents more than 54,500 ha) and cannot be efficiently monitored at low cost. Allowing natural resource managers to concentrate their action on sensitive zone is therefore highly valuable and justifies defining habitats characteristics and constructing risk maps.

6 Conclusion

This study is a first step in assessing naturalized slash pine population dynamics and extent in order to provide a basis for management measures and their prioritization. The feasibility of mapping extensively naturalized pines using partial unmixing techniques applied to satellite images was primarily studied; a MTMF classification was performed on SPOT 5 imagery which is the best data available through DERM. The results were not satisfactory and several issues regarding slash pine spectral signature were highlighted. Future studies will have to investigate if more accurate results can be obtained from SPOT 5 data or other imagery commonly used by Queensland natural resource managers (e.g. Landsat) using other classification methods. Developing techniques based on images that are already available to natural resource managers is preferable for cost and convenience reasons. Other types of imagery, such as AVIRIS or HYPERION data, might however be required to obtain meaningful results. In that case, the cost of the latter has to be taken into account before performing any pilot study to assess the accuracy of the approach retained.

This study also highlighted that extensive mapping of naturalized populations might not be feasible for cost or technical reasons. An alternative approach to prioritize management measures is to determine slash pine habitats preferences based on field survey, the final goal being to predict pine occurrence as a function of different explanatory variables. Instead of knowing where pines are, natural resource managers will know where pines are likely to be. Such an approach has to be based on field studies that are representative from all the areas where slash pines might occur. Another key point is that the explanatory variables retained have to be available for the coastal region of South East Queensland. Indeed, the model has to be applicable to the whole area where pines have a chance to be found (i.e. within a certain distance from the plantations). The approach presented in the study can be reapplied to more accurate data in order to produce risk maps. The latter are a powerful tool since the probability of occurrence, as well as the ecological value, are taken into account. They can be used to prioritize management measures, and therefore implement efficiently preventive and remediation measures despite budget constraints.

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Appendixes

A. Regional Ecosystems and Landzones of Bribie Island

Bribie Island's main Regional Ecosystems and their short description.

	RE	Short description
Landzone 1	12.1.1	*Casuarina glauca* open-forest on margins of marine clay plains
	12.1.2	Saltpan vegetation including grassland, herbland and sedgeland on marine clay plains
	12.1.3	Mangrove shrubland to low closed-forest on marine clay plains and estuaries
Landzone 2	12.2.12	Closed heath on seasonally waterlogged sandplains
	12.2.14	Fore dune complex
	12.2.15	Swamps with *Baumea* spp., *Juncus* spp. and *Lepironia articulate*
	12.2.5	*Corymbia* spp., *Banksia integrifolia*, *Callitris columellaris*, *Acacia* spp. open-forest to low closed-forest on beach ridges usually in southern half of bioregion
	12.2.7	*Melaleuca quinquenervia* or *M. viridiflora* open-forest to woodland on sandplains
	12.2.9	*Banksia aemula* woodland on dunes and sandplains. Deeply leached soils
Landzone 3	12.3.1	Gallery rainforest (notophyll vine forest) on alluvial plains
	12.3.4	*Melaleuca quinquenervia*, *Eucalyptus robusta* woodland on coastal alluvium
	12.3.5	*Melaleuca quinquenervia* open-forest on coastal alluvial plains
	12.3.6	*Melaleuca quinquenervia*, *Eucalyptus tereticornis*, *Lophostemon suaveolens* woodland on coastal alluvial plains

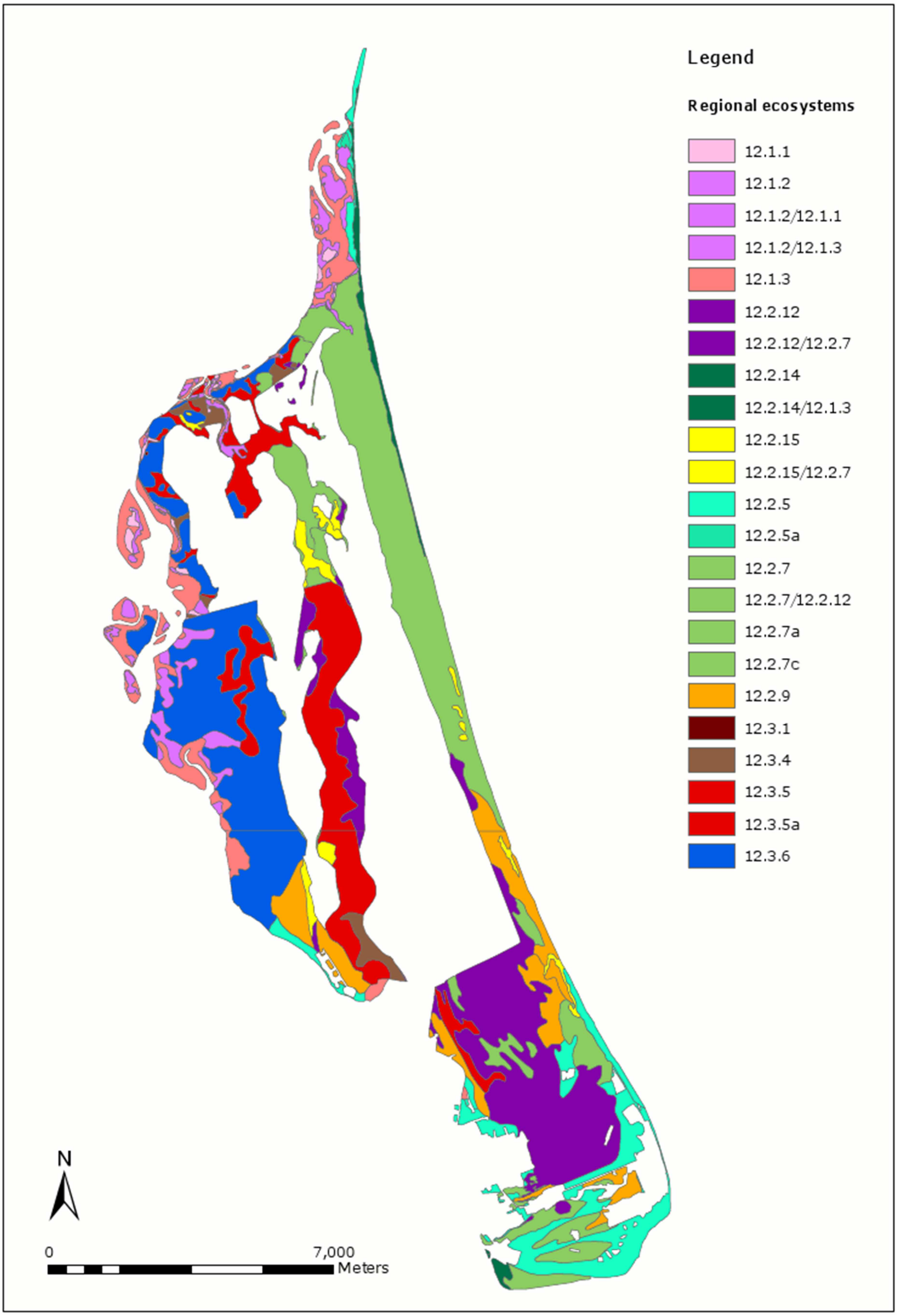
Adapted from Sattler and Williams (1999).

Bribie Island's Lanzones and their short description.

		Short description	General term	
Land Zone 1		deposits subject to periodic tidal inundation	tidal flats and beaches	Quaternary estuarine and marine deposits subject to periodic inundation by saline or brackish marine waters. Includes mangroves, saltpans, off-shore tidal flats and tidal beaches. Soils are predominantly Hydrosols (saline muds, clays and sands) or beach sand.
Land Zone 2		Quaternary coastal sand deposits	coastal dunes	Quaternary coastal dunes and beach ridges. Includes degraded dunes, sand plains and swales, lakes and swamps enclosed by dunes, as well as coral and sand cays. Soils are predominantly Rudosols and Tenosols (siliceous or calcareous sands), Podosols and Organosols.
Land Zone 3		Quaternary alluvial systems	alluvium (river and creek flats)	Quaternary alluvial systems, including floodplains, alluvial plains, alluvial fans, terraces, levees, swamps, channels, closed depressions and fine textured palaeo-estuarine deposits. Also includes estuarine plains currently under fresh water influence, inland lakes and associated dune systems (lunettes). Excludes talus slopes, colluvial deposits and pediments.Includes a diverse range of soils, predominantly Vertosols and Sodosols, also with Hydrosols in higher rainfall areas.

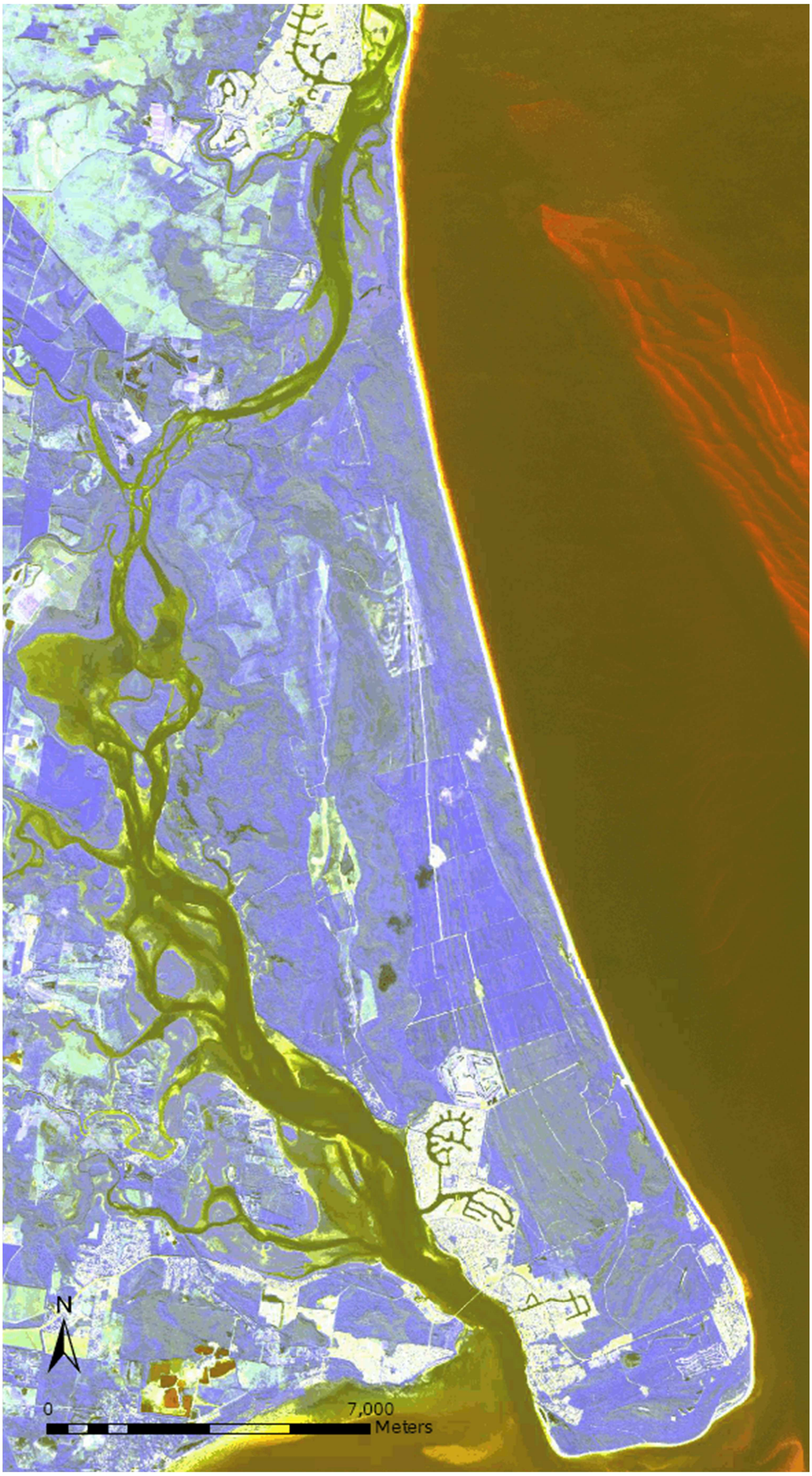
Extracted from Sattler and Williams (1999).

Bribie Island's Regional Ecosystems. Areas belonging to several RE (e.g. 12.12/12.1.1) or to a particular type of a given RE (e.g. 12.2.5a) are represented in the same color as the main RE.



Adapted from Queensland Herbarium (2010).

B. SPOT 5 image (false IR) acquired over Bribie Island (02/07/2009)



C. Spherical densitometer manufacturer's instructions

Spherical densitometer **Model-A**

(An instrument for measuring forest overstory)

Instructions

Hold instrument level, 12''-18'' in front of body and at elbow height is that operator's head is just outside of grid area.

Assume four equi-spaced dots in each square of the grid and systematically count dots equivalent to quarter-square canopy openings.

Multiply the total count by 1.04 to obtain percent of overhead area not occupied by canopy. The difference between this and 100 is an estimation of overstory density in percent. (Assuming each dot to represent one percent is often accurate enough.)

Make four readings per location – facing North, east, South and west – record and average.

Robert E. Lemmon, FOREST DENSIOMETERS
5733 SE Cornell Dr. Bartlesville, OK 74006
(918) 333-2830
Sold through Forestry Suppliers, Inc.

Adapted from manufacturer's instruction.

D. Results of the logistic regression (R output)

```
> glmbin<-glm(pine ~ dis+wind+re, family=binomial)
Message d'avis :
glm.fit: des probabilités ont été ajustées numériquement à 0 ou 1

> summary(glmbin)
Call:
glm(formula = pine ~ dis + wind + re, family = binomial)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.03503  -0.15310  -0.00002   0.00000   2.88352

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -2.004e+01  6.266e+03  -0.003   0.9974
dis         -3.847e-03  1.894e-03  -2.031   0.0422 *
windUWind   -1.431e+01  2.696e+03  -0.005   0.9958
reRE12.1.2   1.871e+01  6.266e+03   0.003   0.9976
reRE12.1.3   3.752e-01  8.887e+03   0.000   1.0000
reRE12.2.12 -4.311e-01  8.419e+03   0.000   1.0000
reRE12.2.14  4.234e+00  8.232e+03   0.001   0.9996
reRE12.2.15 -1.553e+00  9.002e+03   0.000   0.9999
reRE12.2.5   9.079e-01  8.928e+03   0.000   0.9999
reRE12.2.7   8.298e-02  8.435e+03   0.000   1.0000
reRE12.2.9   3.698e-01  8.434e+03   0.000   1.0000
reRE12.3.4   1.763e+01  6.266e+03   0.003   0.9978
reRE12.3.5   1.789e+01  6.266e+03   0.003   0.9977
reRE12.3.6   1.895e+01  6.266e+03   0.003   0.9976
reREnonrem   1.970e+01  6.266e+03   0.003   0.9975
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 218.33  on 649  degrees of freedom
Residual deviance: 123.72  on 635  degrees of freedom
AIC: 153.72

Number of Fisher Scoring iterations: 21


> glmbin<-glm(pine ~ dis, family=binomial)
> summary(glmbin)

Call:
glm(formula = pine ~ dis, family = binomial)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-0.70302  -0.31039  -0.08285  -0.01119   3.03992

Coefficients:
             Estimate Std. Error z value Pr(>|z|)
(Intercept) -1.260588   0.299057  -4.215 2.50e-05 ***
dis         -0.007468   0.001783  -4.188 2.81e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 218.33  on 649  degrees of freedom
Residual deviance: 164.95  on 648  degrees of freedom
AIC: 168.95

Number of Fisher Scoring iterations: 9
```

E. Pre-clearing Regional Ecosystems overlapping plantations

RE	Area (ha)	Fraction	Cum. fraction
12.3.13	25166.07	0.126682	0.126682
12.5.4	18927.78	0.09528	0.221962
12.9-10.4	18407.28	0.09266	0.314621
12.5.12	18125.69	0.091242	0.405864
12.3.5	15014.64	0.075582	0.481445
12.5.10	13724.98	0.06909	0.550535
12.3.4	13632.91	0.068626	0.619161
12.5.9	9930.091	0.049987	0.669147
12.5.11	7868.881	0.039611	0.708758
12.5.4a	6952.59	0.034998	0.743756
12.3.11	5996.716	0.030187	0.773943
12.3.14	3730.162	0.018777	0.79272
12.5.3	3631.09	0.018278	0.810998
12.5.7	3546.99	0.017855	0.828853
12.3.8	3418.395	0.017208	0.846061
12.1.1	3302.985	0.016627	0.862688
12.3.6	3288.394	0.016553	0.879241
12.3.12	2571.693	0.012946	0.892187
12.2.12	2485.348	0.012511	0.904698
12.9-10.14	2029.801	0.010218	0.914915
12.9-10.17	1748.838	0.008803	0.923719
12.3.7	1643.125	0.008271	0.93199
12.2.11	1282.705	0.006457	0.938447
12.3.1	1173.669	0.005908	0.944355
12.1.2	834.6706	0.004202	0.948557
12.1.3	788.2053	0.003968	0.952524
12.9-10.19	700.2411	0.003525	0.956049
12.9-10.1	675.5054	0.0034	0.95945
12.2.7	638.7672	0.003215	0.962665
12.3.14a	609.082	0.003066	0.965731
12.3.5a	575.5264	0.002897	0.968628
12.12.11	557.9992	0.002809	0.971437
12.9-10.17b	554.0697	0.002789	0.974226
12.12.16	529.9849	0.002668	0.976894
12.3.2	495.133	0.002492	0.979387
12.11.16x1	485.3455	0.002443	0.98183
12.9-10.16	337.1298	0.001697	0.983527
12.2.9	327.2949	0.001648	0.985174
12.12.2	265.2927	0.001335	0.98651

RE	Area (ha)	Fraction	Cum. fraction
12.5.1	251.8795	0.001268	0.987778
12.3.4a	229.9294	0.001157	0.988935
12.9-10.3	222.4132	0.00112	0.990055
12.9-10.22	189.6362	0.000955	0.991009
12.3.7d	127.8913	0.000644	0.991653
12.8.8	122.4418	0.000616	0.992269
12.9-10.1x1	111.8321	0.000563	0.992832
12.8.20	107.9077	0.000543	0.993376
12.2.6	100.8478	0.000508	0.993883
12.2.7a	95.46211	0.000481	0.994364
12.2.15	94.19348	0.000474	0.994838
12.9-10.2	94.12992	0.000474	0.995312
12.9-10.14a	87.49568	0.00044	0.995752
12.12.15	85.80965	0.000432	0.996184
12.11.1	74.03725	0.000373	0.996557
12.5.6	73.42171	0.00037	0.996926
12.5.8	63.03045	0.000317	0.997244
12.12.25	55.99455	0.000282	0.997526
12.12.5	50.13932	0.000252	0.997778
12.11.3	50.01044	0.000252	0.99803
12.11.16	49.54574	0.000249	0.998279
12.12.15a	45.84084	0.000231	0.99851
12.5.2	42.74103	0.000215	0.998725
12.12.28	34.55911	0.000174	0.998899
12.5.13	32.69863	0.000165	0.999064
12.5.6c	31.93109	0.000161	0.999224
12.9-10.17a	30.01825	0.000151	0.999375
12.3.11a	25.83684	0.00013	0.999505
12.9-10.21	25.1286	0.000126	0.999632
12.9-10.17d	20.33413	0.000102	0.999734
12.12.14	16.19189	8.15E-05	0.999816
12.9-10.7a	8.048475	4.05E-05	0.999856
12.5.1b	7.530327	3.79E-05	0.999894
12.5.6a	6.792671	3.42E-05	0.999928
12.8.19	3.757224	1.89E-05	0.999947
12.3.7c	2.891716	1.46E-05	0.999962
12.2.8	2.37933	1.2E-05	0.999974
12.2.7c	1.42166	7.16E-06	0.999981
12.9-10.9	1.240657	6.25E-06	0.999987

Adapted from Queensland Herbarium (2010).

F. Pre-clearing Landzones overlapping plantations

Land Zone 9

Short description	gently undulating landscapes on more or less horizontally bedded fine grained sedimentary rocks
General term	undulating country on fine grained sedimentary rocks

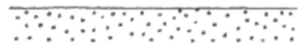
Fine-grained sedimentary rocks, generally with little or no deformation, forming undulating landscapes with a broad range of fine textured soils of moderate to high fertility. Siltstones, mudstones, shales, calcareous sediments, and lithic and labile sandstones are typical rock types although minor interbedded volcanics may occur. Excludes areas of duricrust (land zone 7). Includes a diverse range of soils of moderate to high fertility, predominantly Vertosols, Sodosols, and Chromosols.

Land Zone 10

Short description	plateaus, scarps and ledges with shallow soils on more or less horizontally bedded medium- to coarse-grained sedimentary rocks
General term	sandstone ranges

Medium to coarse-grained sedimentary rocks, with little or no deformation, forming plateaus, ledges and scarps. Includes siliceous sandstones, conglomerates and minor interbedded volcanics, and springs associated with these rocks. Excludes overlying Cainozoic sand deposits (land zone 5). Soils are predominantly shallow Rudosols and Tenosols of low fertility, but include sandy surfaced Kandosols, Kurosols, Sodosols and Chromosols.

Land Zone 5



Short description	plains and plateaus on Tertiary land surfaces, generally with medium to coarse textured soils
General term	old loamy and sandy plains

Extensive, uniform near level or gently undulating Cainozoic plains with sandy or loamy soils. Includes dissected remnants of these surfaces. Also includes plains with sandy or loamy soils of uncertain origin, and plateau remnants with deep soils usually overlying duricrust. Excludes Quaternary alluvial deposits (land zone 3), exposed duricrust (land zone 7), and soils derived from underlying bedrock (land zones 8 to 12). Soils are usually Tenosols and Kandosols, also minor deep sandy surfaced Sodosols and Chromosols. There may be a duricrust at depth.

Land Zone 3

Short description	Quaternary alluvial systems
General term	alluvium (river and creek flats)

Quaternary alluvial systems, including floodplains, alluvial plains, alluvial fans, terraces, levees, swamps, channels, closed depressions and fine textured palaeo-estuarine deposits. Also includes estuarine plains currently under fresh water influence, inland lakes and associated dune systems (lunettes). Excludes talus slopes, colluvial deposits and pediments.Includes a diverse range of soils, predominantly Vertosols and Sodosols, also with Hydrosols in higher rainfall areas.

Extracted from Sattler and Williams (1999).

G. Protected Regional Ecosystems surrounding plantations

Endangered (E) and Of Concern (OC) Regional Ecosystems present in the 500 m buffer zone around South East Queensland slash pine plantations.

RE	Biodiversity status	Area (ha)
12.3.5	OC	1457
12.3.11	OC	1386
12.5.12	OC	1368
12.5.3	E	744
12.3.13	OC	590
12.3.4	OC	535
12.9-10.1	OC	411
12.2.7	OC	374
12.3.2	OC	305
12.8.20	OC	205
12.5.9	OC	190
12.2.7c	OC	166
12.5.11	E	130
12.5.2	E	106
12.11.16x1	E	85
12.3.11a	OC	78
12.9-10.16	E	76
12.3.2/12.3.2	OC	76
12.3.14	OC	65
12.3.1	E	64
12.8.8	OC	54
12.1.1	E	51

RE	Biodiversity status	Area (ha)
12.11.16	E	51
12.3.14a	OC	43
12.3.4a	OC	41
12.2.7a	OC	37
12.9-10.3	OC	36
12.3.12	OC	32
12.3.8	OC	28
12.8.25	OC	14
12.5.13	E	11
12.8.19	OC	10
12.9-10.7a	OC	9
12.9-10.1x1	OC	9
12.3.5a	OC	7
12.9-10.9	OC	5
12.9-10.22	OC	4
12.5.6	E	2
12.5.6a	E	2
12.12.25	OC	2
12.5.6c	E	2
12.9-10.7	OC	2
12.11.14	OC	0

Adapted from Queensland Herbarium (2010).