REMOTE SENSING OF MELALEUCA BIOMASS ON TROPICAL FLOODPLAINS

by

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This thesis is submitted in accordance with the requirements of the degree of

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STATEMENT

I hereby declare that the work herein, now submitted as a thesis for the degree of Doctor of Philosophy by research of Charles Darwin University, is the result of my own investigation, and all references to ideas and work of other researchers have been specifically acknowledged. I hereby certify that the work embodied in this thesis has not already been accepted in substance for any degree.

Dated the 20 April 2005

__________________________________________

Renee E. Bartolo
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ABSTRACT

The major focus of this thesis was to estimate Melaleuca biomass on tropical floodplains using remotely sensed data. The study areas were the Mary Floodplain System, northern Australia, and the floodplains of the Trans Fly Bioregion, southern New Guinea. In order to achieve the major focus, two specific key issues were addressed: the linking of field data to precise locations in remotely sensed imagery; and the selection of an appropriate remote sensing technology for mapping Melaleuca above ground woody biomass. In addressing these two issues, this thesis demonstrates that above-ground woody biomass of Melaleuca species on tropical floodplains can be determined from SAR data.

In determining the factors contributing to the accurate linking of ground data with image data for estimating a biophysical variable (biomass), a spatial statistic was applied to various remotely sensed image data sets. Neither the traditional root mean square error nor the spatial statistics currently employed in remote sensing applications address the problem of spatial registration errors in linking image data with a biophysical parameter on the ground. The statistic used in this study is a local statistic based on the average values within a window of increasing dimensions and assesses the variation occurring through a positional error element. This spatial statistic was used to: firstly, assess the effect of spectral and frequency orientation controls on determining the location and size of field plot sizes from remotely sensed data; and secondly evaluate spatial resolution controls and the impact of locational uncertainty on determining the location and size of field plots.

The results obtained from applying the spatial statistic for estimating an optimal field plot size and location to sample, taking into account positional errors, indicated that the optimal plot sizes and locations varied according to spectral bandwidth (location and width) and polarization (in the case of SAR data). It was shown that the statistic does not simply provide a measure of homogeneity (or conversely heterogeneity), but highlights spatially where the local variance is less than the
global average. Therefore, the boundaries or ecotones of highly variable features and their adjacent habitats are well defined. These ecotone regions are displayed as the largest plot sizes by the statistic.

In relation to spatial resolution controls, the results of this study show that the optimum sample size is dependent on the image data as well as the ground characteristics. The results confirm that the highest resolution data provide the largest scope for selecting suitable plots in the varied environment of the test area only if the spatial registration is comparatively accurate. This fact was highlighted by the ADAR data by using a spatial error of 10 and 50 m. It was clearly demonstrated that the impact of registration error on suitable sample locations is considerable. Using an error estimate of 50 m, there are no areas in the data, where *Melaleuca* could be sampled for a quantitative comparison.

The results of the implementation of the spatial statistic to various image data sets shows that it is important that results from one sensor/image are not transferred to other sensors/images. It is suggested that the spatial statistic is implemented at the outset of any remote sensing investigation that links image data with field data relating to biophysical parameters.

It was determined through an extensive literature review that quad-polarised SAR data was the most suitable remotely sensed data by which to estimate above ground woody biomass of *Melaleuca* habitats in tropical floodplain environments. It is clear that the P-HV channel is most suitable for this task, as the L-Band channels are susceptible to saturation effects at lower biomass levels and the co-polarised P-band channels appear to be affected by understorey responses. The results of the JERS-1 analysis show some promise for examining *Melaleuca* encroachment in the Trans-Fly Bioregion. However, these results are not conclusive due to the time lag between the acquisition of image and field data, and the dynamic nature of the environment. There is the potential to use future space borne L-Band sensors with quad-polarisation for this task.
This study has also demonstrated that quantifying biomass relies on accurately locating sites and determining an appropriate plot size for field sampling. This was achieved through implementing the spatial statistic. The poor results obtained from the transect/point data highlight the importance of linking ground and image data in terms of plot size and location.

This research has formed a basis for further development of models and research related to quantifying the above ground biomass of wetland forest habitats in the tropics of the northern Australia and New Guinea. With the impending launch of JAXA’s ALOS satellite system late in 2005, there is the opportunity to obtain L-HH and L-HV data at 10 m resolution for the study regions. This will enable further SAR data capture for the Trans Fly Bioregion site, and field sites within the region to be collected using the spatial statistic. A suitable regression model can then be established using multi-date imagery. With a robust model, it is assumed rapid *Melaleuca* encroachment with the study region can be effectively quantified and monitored. Further work can be conducted on the effect of understorey composition and flooding on SAR backscatter. In future investigations, dry sites need to be incorporated more fully. The effect of understorey composition (aquatic grasses) needs to be examined in more detail also. Finally, the input of the above ground woody biomass model in the Mary Floodplain system could be linked with biogeochemical models relating to methane and carbon. These biogeochemical models do not exist at present but it is a relevant future research direction that would contribute to furthering the knowledge we have on the role of the remote floodplains of tropical northern Australia.
ARTICLES AUTHORED AND CO-AUTHORED BY RENEE BARTOLO

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CHAPTER ONE

1. INTRODUCTION

1.1. PROJECT DEFINITION

This thesis deals with the problems involved in mapping *Melaleuca* biomass on tropical floodplains using remote sensing data for test sites in northern Australia and New Guinea. The primary remote sensing data used for mapping was Synthetic Aperture Radar (SAR). SAR is an active microwave remote sensing system that is able to penetrate cloud cover and capture images during the day or night. Other data used in the project, but not for the specific purpose of biomass mapping were optical remote sensing data such as Landsat Thematic Mapper (TM), MODIS/ASTER airborne simulator (MASTER) (developed for the Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] and Moderate Resolution Imaging Spectroradiometer [MODIS] projects), and Airborne Data Acquisition and Registration (ADAR) digital aerial photographs.

The following sections of this chapter present the focus of the study and the contribution this thesis makes to understanding land cover dynamics in tropical floodplains.

1.1.1. Focus of this study

The focus of this study is mapping *Melaleuca* species biomass on tropical floodplains. In concentrating on this, the thesis addresses the broader methodological issues associated with accurately estimating above ground woody biomass in topical wetland environments. Specifically two key issues are addressed: the linking of data collected on the ground to precise locations in remotely sensed imagery; and the selection of an appropriate remote sensing technology for mapping *Melaleuca* biomass.
The first major challenge in this study is measuring biomass at a specific location on the ground and being able to precisely locate that field measurement on the imagery. Traditionally, there is a degree of spatial uncertainty when linking the ground and image data. That is, field data from a given location on the ground may be correlated to a pixel in the image that may be one or more pixels away from that ground location.

Isolated tropical environments, such as those presented in this thesis, present the remote sensing scientist with a range of obstacles related to spatial uncertainty. Errors can be introduced to the mapping process throughout many stages of the project (Haining and Arbia, 1993; Kiiveri, 1997; Foody, 2001; Chen et al., 2004). Often, such areas have not been surveyed in detail and only small-scale maps are available. The geo-rectification of remotely sensed data is therefore difficult, due to the mis-match in scale. Maps of isolated tropical areas can also be out dated, and in the case of wetlands, finding reference points in the image may be difficult due the dynamic nature of the environment (e.g. river morphology changes). In addition, field locations recorded by a handheld Global Positioning System (GPS) are only accurate to approximately 5-20 m (with selective availability disabled). Therefore, the geo-rectification of an image to small-scale map coordinates and field measurements will not be accurate. It is also difficult to precisely locate a GPS position on the image. For example, Figure 1.1 shows that a precise point within a fork of a river on the ground may represent a choice of 6 pixels in a Landsat TM image.

Given these difficulties associated with ground truthing in tropical wetlands, it was necessary to develop a robust methodology for integrating ground data with image data sets of various spectral and spatial resolutions. Correlating image with ground data is examined in this thesis in detail by investigating spectral (wavelength using optical remote sensing data), frequency orientation (polarimetric SAR) and spatial resolution controls in imagery within a specified (realistic) spatial error. This was achieved through the development and application of a spatial statistic, which determines the appropriate field plot size at any given location in an image.
The next phase of the project involved an assessment of remote sensing technologies for estimating biomass. Synthetic Aperture Radar (SAR) data were selected as the appropriate medium, and where possible, the use of SAR data was coupled with the implementation of the spatial statistic to collect appropriate field data.

1.1.2. Thesis contribution

This thesis addresses gaps in knowledge related to: methods in inventory and management of key tropical wetland communities; biomass estimation of *Melaleuca* species; Synthetic Aperture Radar (SAR) mapping; and methods in linking ground data and image data with location being a major source of uncertainty.

Forested wetland communities such as *Melaleuca* floodplain forests, play a vital role in the hydro-geomorphic functioning of wetlands (Gurnell, 1997). In terms of tropical wetland inventory and management, it is crucial to have a detailed knowledge of where key communities are, and monitor these areas over time (Finlayson, 1999). Estimations of wetland community biomass using remote sensing technology, particularly for remote and relatively unpopulated regions, can provide wetland managers with a useful measure of habitat change. This is particularly the case for the conversion of open swamp to swamp forest landscape via the encroachment of woody vegetation (as seen in southern New Guinea) (Bartolo *et al.*, 2002), or swamp forest dieback through processes such as saline intrusion (as evidenced in northern Australia) (Whitehead *et al.*, 1990). This thesis provides a methodology for monitoring the extent and biomass of forested wetland communities in tropical regions.
Figure 1.1: Katmer, Papua New Guinea. Landsat 5 TM image displayed as R,G,B: 5,4, 3 (left) and ground photograph of Katmer (right). Katmer is the junction between the Torassi River and Katmer Creek. When examining the Landsat data at the pixel level it is difficult to determine which pixel is actually representing the junction in reality.
To date, very little work has been conducted on *Melaleuca* communities in the tropical wetlands of northern Australia and New Guinea. This is perhaps due to the remoteness and relative inaccessibility of these environments for large parts of the year and that proportionally, *Melaleuca* habitats are not the dominant vegetation type. However, *Melaleuca* dominated communities are bio-indicators of the dynamics and environmental change in coastal and floodplain environments (Bell *et al.*, 2001). Therefore, *Melaleuca* may be used to monitor floodplain health in terms of environmental and climatic impacts on tropical wetlands. This thesis provides a method for successfully examining *Melaleuca* biomass using remote sensing technology. The mapping product produced from this method can be incorporated into biogeochemical modeling of the floodplain environments.

There have been a number of studies examining the use of SAR to map the biomass of forested wetlands in the tropics. These are discussed in Chapter 2. However, most of these have been for Central and South America. There have been no studies for this application in northern Australia and New Guinea. This thesis contributes to the body of knowledge on the applications, advantages and limitations of remotely sensed data and in particular SAR technology for mapping tropical forested wetlands to areas where it has previously not been applied.

Finally, as discussed in Section 1.1.1, this thesis presents a methodology for determining the optimum plot sizes and locations for ground sampling and subsequent linking to remotely sensed imagery. The methodology differs from previous work in this area because both plot size and location, is determined. A unique feature of the methodology suggested in the current study is that it identifies candidate sites for locating sample plots. The spatial statistic employed in this study is an extension of the local variance suggested by Woodcock and Strahler (1987). The modification in the methodology adopted in this thesis is to expand the window of analysis based on the magnitude of the anticipated registration error.
1.2. BACKGROUND CONCEPTS

It is important to define the terms “wetland” and the “tropics” in order to provide a characterisation of the environment in which this research was conducted. Wetlands are commonly defined using the Ramsar Convention (1971) definition:

"wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent of temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.” (Usback and James, 1993:2)

This Ramsar definition is very broad, therefore, in the context of this thesis, wetlands are defined as:

“a vegetation area which is flooded, either permanently or seasonally.” (Denny, 1985:1).

The tropics are defined as the region of the earth between the Tropic of Cancer (23°28’N) and the Tropic of Capricorn (23°28’S) and this equates to 50 M km² of land surface area. This land surface includes Africa, Central and South America, Asia and Australia. One key feature distinguishing the wet-dry tropics from temperate regions is that wet-dry tropical regions are subject to the monsoons.

Tropical wetlands are diverse and unique in their ecological role and functions. Collectively, they represent a myriad of wetland habitats from the forested wetlands of the Amazon, to the reed swamps of Africa, and support a vast array of species, often endemic to these wetlands. The functions these habitats provide are wide-ranging, supplying ecosystem services and benefits not only to local people, but also to the global community as a whole. Tropical wetlands, specifically, are biodiversity hotspots (Junk, 2002). Some of the services wetlands provide are extracted from the goods and services for natural and semi-natural ecosystems described by de Groot et al. (2002) and include:

• gas regulation services (e.g. maintenance of air quality);
• climate regulation services (e.g. maintenance of climatic parameters such as temperature and precipitation favourable for human activities);
• disturbance prevention services (e.g. flood prevention);
• water regulation services (e.g. drainage and natural irrigation);
• water supply services (e.g. water for consumptive use);
• soil retention and formation services (e.g. maintenance of arable land and productivity);
• waste treatment services (e.g. filtering of pollutants and detoxification);
• refugium services (e.g. maintenance of biological and genetic diversity);
• nursery function services (e.g. maintenance of commercially harvested species); and
• supply of food (e.g. subsistence farming and aquaculture).

For the past ten to fifteen years there have been numerous efforts to value the environmental functions and benefits of tropical wetlands (Barbier, 1993; Barbier, 1994; Costanza et al., 1997). A total valuation of the Bintuni Bay mangroves in West Papua, Indonesia derived a value of US$1500 km$^{-2}$ as a ‘capturable’ biodiversity benefit if the mangroves were left intact (Ruitenbeek, 1992)

In a global sense, tropical wetlands are an environment under threat. The long-term environmental trends and the future of tropical wetlands have been examined by Junk (2002). He proposes that one of the key reasons this ecosystem is so threatened is due to the belief tropical wetlands are free and non-exhaustive supplies of land and water and are therefore utilized in this manner. This belief system and resultant exploitation is being driven by a rapidly increasing population base throughout the tropical region coupled with modernisation of food production, water use and wetland reclamation (Scott and Poole, 1989). Junk (2002) identifies the dominant threats to tropical wetlands as: high rates of population growth; economic and political development; demand for water and hydroelectric energy; eutrophication and pollution caused by poor wastewater treatment practices; agriculture and animal ranching causing large-scale changes in vegetation, hydrology and sediment input; global climate
change; and invasion by exotic species. Analysis of key indicators such as demographic, political, economic and ecological trends until 2025, suggests stable conditions for wetlands in tropical Australia whilst predicting serious threats for the remaining wetlands in tropical Asia (Junk, 2002).

1.2.1. Tropical wetlands of Australia and its near neighbours

In terms of tropical Australia’s immediate neighbours, there is a scarcity of Ramsar wetlands listed in the Directory of Wetlands of International Importance (Frazier, 1999). The criteria for identifying wetlands of international importance are in terms of groups:

- Group A; sites containing representative, rare or unique wetland types; and
- Group B; sites of international importance for conserving biological diversity with criteria specifically based on species and ecological communities, waterbirds and fish.

In tropical Australia there are eight sites, whilst there are only four sites in Indonesia and Papua New Guinea (see Figure 1.2). These figures highlight the disparities between ‘developed’ and ‘developing’ countries in regards to their ability to adopt conservation measures due to economic, political or population pressures.

Indonesia has two Ramsar listings covering 242 700 hectares. Berbak located in eastern Sumatra is the largest and only protected peat swamp in Sumatra. It occupies 162 700 hectares making it one of Southeast Asia’s largest and undisturbed peat swamps. The integrity of the swamp is threatened by drainage canals, illegal logging of some of the 150 tree species existing on the site, and forest fires resulting from uncontrolled burning of agricultural land on the fringes of the site (Frazier, 1999). The second listing is Danau Sentarum, an 80 000 hectare complex of seasonal freshwater lakes, riverine floodplains, freshwater swamp forest and peat swamp forest. It contains a large area of primary freshwater swamp, which is possibly the largest representative example
of this habitat in the Greater Sunda islands. Some of the threats to this site include dry season burning of vegetation, traditional harvest of forest products, which may be occurring unsustainably, and poisoning as a fishing method (Frazier, 1999).

Papua New Guinea’s two Ramsar sites encompass almost 600,000 hectares. The largest, Tonda Wildlife Management Area is one of the project sites addressed in this thesis and will be discussed in detail in Chapter 3. The other site is Lake Kutubu located in the southern highlands. The site covers 4,924 hectares and is dominated by a permanent freshwater lake (PNG’s second largest lake) fringed by reed-dominated swamp (Frazier, 1999). There is also a subterranean cave hydrological system present. The major threat to Lake Kutubu is increased migration to the area which has the potential to introduce exotic aquatic plants and animals to the system.

In comparison to other countries such as the United States of America and India, Australian tropical wetlands, as a whole, have not been exposed to the same level of human impact and remain relatively unmodified (McComb and Lake, 1990; Junk, 2002). Therefore, Australian wetlands and particularly those of northern Australia are of international significance. Located within the ‘Top End’ (a colloquial term for the northern coastal region) of the Northern Territory are three Ramsar listed sites and 12 coastal wetland complexes which are listed in the Directory of Important Wetlands of Australia (Whitehead and Chatto, 1996). The most dominant type of wetland in the nationally important wetlands listed for the Northern Territory is ‘freshwater swamp forest’ (Whitehead and Chatto, 1996). Despite this dominance, little research or management priority has been given to the freshwater swamp forests, of which *Melaleuca* forests are the dominant community.
Figure 1.2: Ramsar listed sites located within the tropics of Australasia (Australia, Papua New Guinea and Indonesia)
1.2.2. *Melaleuca* species on Tropical Floodplains

The genus *Melaleuca* is a Gondwanan group of trees belonging to the family Myrtaceae, and contains approximately 250 described species (Barlow, 1988), with the possibility of undescribed species existing in remote northern Australia (Boland *et al*., 1984). There are 20 species of *Melaleuca* present in the Northern Territory (Cowie *et al*., 2000). The name “*Melaleuca*” originates from the Greek *melas* (black, dark) and *leucon* (white), a reflection of the bark colouring (white with a black stocking) (Boland *et al*., 1984), which is the result of seasonal fire and seasonal inundation (see Figure 1.3). The common name for the larger species of this genus is “paperbark”, reflecting the distinctive “papery” bark. This type of bark is an adaptation to poorly drained conditions (inundation) with internal longitudinal air passages developed through the collapse of spongy tissue within each layer (Cowie *et al*., 2000).

There are three dominant species of *Melaleuca* commonly found on tropical floodplains: *M.viridiflora* Sol. Ex Gaertner; *M.cajuputi* Powell; and *M. leucadendra* (L.) L. *M. quinquenervia* also occurs in the tropics of New Guinea and eastern Queensland. Hybrids of *M.viridflora* and *M.leucadendra* are common.
The *Melaleuca* genus as a whole has been utilized for various purposes. Aboriginal people have used the bark for wrapping babies, as bedding (Boland *et al*., 1984), in the construction of shelters, for cooking (wrapping or carrying) food, and in some instances as torches (Cowie *et al*., 2000). The bark has also been used as washable mattress and pillow fill (Boland *et al*., 1984). The bark is also in great demand for lining hanging wire baskets in urban gardens (Boland *et al*., 1984). The leaves of *Melaleuca* spp. have been used by Aboriginal people throughout Australia as medicine for coughs, headaches and generalized aches, whilst the bark has been used as bandages (Isaacs, 1987). Specifically, *Melaleuca cajuputi* leaves are prepared as a liquid body wash for aches and pains, including constipation; *Melaleuca leucadendron* leaves are used as a decongestant, inhalant and liniment, and the bark is pounded and soaked in warm water to be used as a beverage or wash to treat colds and headaches (Isaacs, 1987). Aboriginal people also use *Melaleuca* as a source of drinking water (Cowie *et al*., 2000), by tapping the trunk. *M. cajuputi* has also been used by Aborigines for dugout canoes (Cowie *et al*., 2000).
The distribution of *Melaleuca* varies greatly between floodplains in the Top End (Cowie *et al*., 2000). Some of these floodplains support extensive wooded swamps (e.g. The Mary River Plains and the Arafura Swamp) whilst others contain paperbark fringing forests. There is a strong link between wetland vegetation patterning and geomorphology (Whitehead *et al*., 1990; Wilson *et al*., 1991; Woodroffe and Mulrennan, 1993), however, geomorphological differences between wetland systems do not explain this variation in *Melaleuca* distribution (Cowie *et al*., 2000). In contrast, the distribution of *Melaleuca* species within the same floodplain is controlled by flooding and salinity tolerance (Cowie *et al*., 2000).

90% of Australia’s *Melaleuca* forests occur in northern Australia and cover in excess of 3.7 million hectares. The majority of the northern *Melaleuca* forests are large areas of low woodlands situated on coastal floodplains and seasonal swamps (National Forest Inventory in the Bureau of Rural Sciences, 2003). Figure 1.4 shows the spatial extent of these *Melaleuca* woodlands, which are remote and often inaccessible for the greater part of the year.
1.2.3. Remote Sensing of *Melaleuca* species on Tropical Floodplains

Identification and quantification of *Melaleuca* habitat is a key element in floodplain management of the wet/dry tropics as it is a significant bio-indicator of environmental change in floodplain environments (Williams, 1984; Bell *et al*., 2001). At present, there is a lack of current and accurate maps of *Melaleuca* habitat for northern Australia and there are no freely available maps for the Trans-Fly Bioregion in New Guinea. In the Northern Territory, there are a few floodplain vegetation maps available for particular areas, the Mary Floodplain
System being one of them (see Lynch, 1996). In order to monitor landscape change (particularly in the Trans-Fly) and floodplain health, it is necessary to produce a current baseline map indicating the areal extent of *Melaleuca*, and if possible habitat type. Remote sensing technologies offer a potential solution for this task.

The primary remotely sensed data sources used for *Melaleuca* mapping in northern Australia have been Landsat TM and aerial photography (Williams, 1984; Lynch, 1996; Bell *et al*., 2001; Harvey and Hill, 2001; Heerdegen and Hill, 2002; Riley and Lowry, 2002). A vegetation map for the Mary River Floodplains was produced in 1996 using both Landsat imagery and colour infrared aerial photography at a scale of 1:50 000 (Lynch, 1996). An unpublished 1993 *Melaleuca* survey was used as ancillary data. This is the most current vegetation map for the floodplains and contains numerous *Melaleuca* classes. In a study mapping the vegetation of Melacca Swamp (Harvey and Hill, 2001), the use of aerial photography was found to produce more detailed vegetation maps compared with SPOT XS and Landsat TM imagery. Changes in the density of *Melaleuca* swamp forest have been used as an indicator of floodplain stability on the Magela Floodplain in Kakadu National Park (Williams, 1984). Aerial photography acquired in 1950 and 1975 was analysed for the establishment of baseline floodplain changes prior to the commencement of Ranger uranium mine in 1979. This work was further extended by Riley and Lowry (2002) to analyse changes within the same site using aerial photography from 1975 and 1996. SAR data in the form of AirSAR (Bell *et al*., 2000; 2001) and SIR-C (Hess, 1999) have been used to delineate *Melaleuca* habitat on floodplains. Bell *et al*. (2000; 2001) successfully mapped salinity affected stands of dead *Melaleuca* in the Alligator River Region of Kakadu National Park and in the Mary Floodplain System by fusing Landsat TM and AirSAR data.

Remote sensing of *Melaleuca* on tropical floodplains is not without complications. The first attempts at mapping *Melaleuca* in tropical wetlands were conducted in South Florida, United States of America, where *Melaleuca* is an introduced invasive species. It was rapidly identified that there was no unique spectral signature for Melaleuca in Landsat imagery (Capehart *et al*., 1977). The
reasons presented by the authors for spectral reflectance variability include: trees are located in a wide variety of sites; trees can occur in various degrees of mixture with other floodplain species; and trees occur in widely varying densities and size classes. Subsequent studies of Melaleuca mapping in South Florida have found colour infrared photography can delineate stands in sufficient detail for further mapping (Arvantis and Newburne, 1984; McCormick, 1999). In the context of northern Australia, further problems arise due to spectral overlap between Melaleuca, mangroves and riparian or monsoon forest. SAR data may offer better delineation of Melaleuca communities due to the fact that the trees are structurally different to other species in the floodplain environment.

1.3. RESEARCH OBJECTIVES AND APPROACH

The main aim of this project is to assess Melaleuca biomass on tropical floodplains in remote regions of Australasia using remotely sensed data. The following research question was proposed to address the aim:

1. Can above ground woody biomass of Melaleuca species on tropical floodplains be determined from remote sensing data?

In order to address this research question, the issues of spectral (wavelength), frequency orientation (polarimetric SAR) and spatial resolution controls in relation to spatial error within remotely sensed data needed to be addressed, so that ground data could be linked with remotely sensed data to accurately estimate above ground biomass of Melaleuca species. As a result, a spatial statistic was developed for the classification of a continuous variable, which in this project is biomass. The project objectives and approach for achieving this are described in sections 1.3.1-1.3.4.
1.3.1 What factors contribute to accurately linking ground data and image data for quantitative applications?

A review of the existing literature (see Chapter 2) has shown that issues of spatial uncertainty between field collected and remotely sensed data for quantitative applications have not been adequately addressed. This specifically relates to determining the most appropriate field plot size for field data collection in order to account for locational uncertainty and image variance.

The approach taken here was to develop a spatial statistic to determine appropriate field plot size and examine how this relates to spectral and spatial resolution controls. Studies estimating relationships between the field sampled information and remote sensing imagery (and vice versa) assume that locational error between these data sets is minimised; however in many instances this remains unquantified. In order to overcome locational and measurement uncertainties between remote sensing and field data it is necessary to determine an appropriate plot size for field sampling. This has been achieved in the past using various methods which have been summarized in Chapter 2.

The analysis process used data collected for the lower catchment of the Mary Floodplain System, a tropical wetland environment in the Northern Territory, Australia. Results are presented for small sample areas that contain the major land cover types that are characteristic of the environment and have proved problematic in sampling in the past, or have been assumed to be homogenous in terms of image data.

1.3.2 Assess the effect of spectral (wavelengths for optical and SAR data) and frequency orientation (polarimetric SAR) controls on determining the location of suitable field plot sizes.

When conducting a quantitative remote sensing study it is necessary to determine the applicability of available spectral regions (location and bandwidth) for the application. When quantifying biophysical parameters using deterministic
or empirical approaches, the information contained in one spectral bandwidth (and polarisation as is the case for polarimetric radar) will vary in comparison to other spectral bandwidths/centres because each reacts differently with target objects on the ground. For example, in biomass estimation for woody forests, P-HV (P Band with Horizontal transmit and Vertical receive polarisation) displays a higher correlation than L-HH or P-HH (Israelsson et al., 1994; Rauste et al., 1994; Hoekman and Quinones 1998). Atkinson and Emery (1999) state that spatial variation in a remotely sensed image can differ both in amount and scale between wavelengths. It is this spatial variation that is crucial to take into account when field sampling.

In this project, wavelength controls were investigated using both airborne MASTER and Topographic Synthetic Aperture Radar (TOPSAR) data. Polarisation controls were examined utilising TOPSAR data.

1.3.3. Evaluate spatial resolution controls and the impact of locational uncertainty on determining the location of suitable field plot sizes.

Along with spectral resolution, spatial resolution is one of the most important characteristics of remote sensing systems, especially in relation to recent developments in high-resolution sensors. A review of spatial resolution and its impact on field sampling is presented in Chapter 2.

There are many types of measurement error that impact on remote sensing studies. Curran and Hay (1986) group the measurement errors into three categories: errors in the measurement of ground variables; error in the measurement of remotely sensed variables (which relate specifically to optical sensors); and errors in the physical correlation of ground variables and remotely sensed variables. Of most importance in the context of this study are errors associated with the physical correlation of ground variables and remotely sensed variables. There are two types of error that fall into this category. The first is error related to misregistration in space whereby remotely sensed data from
airborne and satellite sensors are associated with an inherent locational error. The second error is associated with *misregistration in time* (Curran and Hay, 1986; McGwire *et al.*, 1993). This error refers to the fact that the remotely sensed data and ground data that it is related to may not have been measured at the same time. This can significantly impact on the assessment of biophysical variables that may change rapidly. The spatial statistic developed in the current research addresses the error of misregistration in space.

Spatial resolution effects were investigated using: the NIR channel of airborne ADAR data acquired at 50 cm and 1 m pixel sizes; Band 9 (NIR) of airborne MASTER data at 20 m resolution; and the NIR channel (Band 4) of Landsat ETM data at 30 m resolution. Locational error for these datasets varied according to the data type and error estimates as described in Chapter 5.

1.3.4. Determine the above ground woody biomass of *Melaleuca* on tropical floodplains using the most appropriate remotely sensed data.

Numerous remote sensing technologies have been investigated in estimating the above ground biomass of forests. These technologies are reviewed and assessed for their applicability to this project (Chapter 2). A comparison of sensors, examining saturation levels for measuring forest biomass and developing data limitations from the literature indicated that Synthetic Aperture Radar (SAR) was the most appropriate technology to utilize for assessing *Melaleuca* habitats on floodplains.

A comparison of SAR sensors is also conducted as the availability of SAR data for the study areas differed. NASA’s (National Aeronautical Space Administration) JPL (Jet Propulsion Laboratories), multi-frequency polarimetric TOPSAR data was used for the Mary River Floodplain, whilst JAXA’s (Japanese Aerospace Exploration Agency) JERS-1 single frequency/polarization data was used for the Trans-Fly site. This has important implications for monitoring biomass on remote floodplains over time, as the TOPSAR system is airborne
(greater expense to acquire), whereas the JERS-1 data was satellite borne (less expensive to acquire).

The use of TOPSAR data, primarily polarimetric L-Band (24 cm / 1.25 GHz) and P-Band (65 cm / 440 MHz) frequencies enabled the assessment of the most suitable frequency and polarization for estimating biomass of Melaleuca species. In addition, the effect of understorey flooding was able to be examined at the Mary River site because mixtures of wet and dry sites were sampled in the field.

1.4. THESIS OVERVIEW AND CHAPTER OUTLINE

The research topic of this thesis is to estimate above ground woody biomass of Melaleuca species on tropical floodplains in the Northern Territory, Australia, and the Trans Fly Bioregion of southern New Guinea, using remote sensing technology. The project develops a methodology for accurately assessing Melaleuca biomass on tropical floodplains in remote regions through successfully linking ground data with image data.

This thesis is divided into eight chapters. Chapter 2 provides a review of relevant literature and is divided into two main components. Firstly, the need for biomass estimation is explored followed by a review of the literature relating to biomass estimation using remotely sensed data. The limitations of particular technologies in the context of the research topic are discussed. Secondly, issues of uncertainties in linking ground data with image data are summarized along with existing methods for examining spatial error within this context. Chapter 3 describes the study areas in detail, with a particular focus on the Trans Fly Bioregion sites where little scientific work has been conducted. Chapter 4 introduces the research design implemented and provides a detailed examination of the data sources including, ADAR, Landsat, MASTER, TOPSAR and JERS-1 image data. Chapter 5 discusses the methodology adopted in this project. Chapter 6 presents the results from analysis of: firstly, a methodology to link ground data and image data taking into account spatial error; and secondly, the estimation of above ground biomass of Melaleuca in the study areas. Chapter 7 provides a
technical discussion of the results and evaluates the methodology developed. Chapter 8 consists of a summary of the thesis and future directions for the research presented.
CHAPTER TWO

2. LITERATURE REVIEW

This chapter presents a literature review on issues in the linking of remotely sensed data with field data, methods of determining spatial structure in remotely sensed imagery, and the use of remotely sensed data for estimating above ground woody biomass.

2.1. ISSUES TO BE CONSIDERED WHEN LINKING REMOTELY SENSED DATA WITH DATA COLLECTED IN THE FIELD

Nearly all remote sensing investigations related to the earth’s surface require some form of knowledge of the ground, which is usually provided through field sampling (Atkinson, 1991). Conducting meaningful fieldwork for remote sensing applications in remote tropical wetland environments often proves difficult. There are many inherent characteristics of the wetlands that complicate the collection of field data that is to be used for empirical remote sensing studies. Firstly, tropical wetland environments are heterogeneous at multiple spatial scales, characterised by subtle ecotones, which may result in sampling an ecotone rather than the target habitat. This results in mixed pixels that contain a variety of ground objects. The theory that a remotely sensed image is a model of the earth’s surface at that location and the reality of this has been addressed on numerous occasions (Curran and Hay, 1986; Woodcock and Strahler, 1987; McGwire et al., 1993; Raffy, 1993; Cracknell, 1998). Secondly, georeferencing of remote sensing imagery to sub-pixel scales is problematic in heterogeneous (remote) natural environs due to the absence of readily identifiable landmarks such as roads or clearly defined forks in rivers. Therefore, there may be no means or a reduced means to establish a link between field and image coordinates. Studies estimating relationships between the field sampled information and remote sensing imagery (and vice versa) assume that locational error between these data sets is minimised, however in many instances this remains unquantified. Campbell and Browder (1995) addressed the issue of locational uncertainty in field data collection by using field sketches, however
the error still remained unquantified. In order to overcome locational and measurement uncertainties between remote sensing and field data it is necessary to determine an appropriate plot size for field sampling. This has been achieved in the past using various methods which are summarised further on in this section.

Types of measurement error were presented in Chapter 1. Implementing the use of ground control points can significantly reduce spatial misregistration error, however a certain degree of error will always remain. The magnitude of this error is dependent on the registration procedure and is usually indicated by a root mean square error (RMSE) derived from control points between images, map features or ground points. As suggested previously, this error can be significant in natural environments, where ground control points are often not well defined. Even with RMSE values less than half a pixel, misregistration errors of one pixel or more may still occur as the RMSE is based on the number and distribution of points used (Phinn and Rowland, 2002). The locational error combined with the effect of image blur impacts on the error of Radiance measurements (Curran and Hay, 1986; Curran and Williamson, 1986; McGwire et al., 1993), which is particularly problematic when the spatial frequency of the environment is high in comparison to the spatial resolution. Curran and Hay (1986) suggest that measurements should be acquired for homogenous regions that cover an area of at least 3 x 3 pixels. This represents a relatively large area when considering the ground resolution element (GRE) of a sensor at 80 metre spatial resolution is at least 6 400 m² without taking into account the locational error and image blur (Curran and Williamson, 1986). Atkinson (1991) further suggests enlarging the GRE to account for uncertainty in pixel location and convolution caused by the point spread function (PSF) of the sensor.

Along with spectral resolution, spatial resolution is one of the most important characteristics of remote sensing systems, especially in relation to recent developments in high-resolution sensors. When investigating issues of spatial resolution in a remote sensing context, researchers frequently refer to the “size of the support” (Atkinson and Curran, 1995) or “support size” (Wang et al., 2001). The size of the support is defined by the size, geometry and orientation of
the space over which a measurement or observation is made, and is theoretically equivalent to the spatial resolution (Atkinson and Curran, 1995). More importantly it denotes the plot size for field data collection (Wang et al., 2001). However, due to the PSF of the sensor, the true size of the support is greater than the spatial resolution and also varies across an image scene as a result of the sensor’s scan angle (McGwire et al., 1993; Atkinson and Curran, 1995).

Many remote sensing investigations that rely on ground data to verify results do not report in detail sampling regimes and the way in which sample sites were selected. Campbell and Browder (1995:333) state that the collection of field data for remote sensing studies is one of the “least systematised aspects of the field”. Often the size of the samples has been determined by the resources available (Webster et al., 1989). Atkinson and Curran (1995) highlight this point stating that if the cost of measurement increases with the size of the support, small supports should be used. However, if the size of the support has no impact on cost of measurement, then the size of the support should be as large as possible. This is because a high degree of variability within a remotely sensed image requires a large sample to adequately capture this variance (Webster et al., 1989). A remotely sensed image represents a complete spatial population (Curran and Williamson, 1986) with individual pixels as members of the population. The majority of ground surveys conducted for the purpose of verifying remote sensing data are random samples of points or small areas. A mean value is calculated for the point or area that is then applied to the whole pixel (Curran and Hay, 1986).

2.2. DETERMINING SPATIAL STRUCTURE FROM REMOTELY SENSED IMAGERY

Choosing appropriate spatial resolution and field sampling dimensions (the support size or plot size) using image-variance based methods has been addressed by various researchers (e.g., Townshend and Justice, 1988; Marceau et al., 1994a,b; Dungan et al., 1994; Phinn et al., 1996, 2000; Holopainen and Wang 1998; Atkinson and Curran 1997; Menges et al., 2001). An overview of
spatial statistics is given by Atkinson (1999). The spatial dependence inherent in remotely sensed data means that the majority of classical statistical methods are inappropriate unless modified accordingly (Unwin and Unwin, 1998). The semi-variogram is most frequently used in remote sensing applications to identify the overall structure of an image and autocorrelation within the data (Curran, 1988; Woodcock and Strahler, 1987; Ramstein and Raffy, 1989; McGwire et al., 1993; Wulder and Boots, 1998). The semi-variogram and kriging methods have been used to identify a sampling strategy, which ensures that ground samples are spatially independent (Atkinson, 1991; Atkinson and Curran, 1995; Curran and Atkinson, 1998; Atkinson et al., 2000). The semi-variogram has also been used as a textural classifier (Miranda et al., 1996) in the context of a local area statistic. Wulder and Boots (1998) present an overview of spatial statistics in the remote sensing context and use the Getis statistic (Getis and Ord, 1992) to assess the strength of inter-pixel relationships, as well as the magnitude of the autocorrelation in the data. In determining an appropriate spatial resolution for satellites designed to monitor global changes in land cover, Townshend and Justice (1988) used Fourier analysis and scale variance analysis. Wang et al. (2001) addressed the problem of choosing an appropriate plot size to validate image classification using regional semi-variograms. An alternative to kriging is conditional simulation (also known as stochastic simulation/imaging) and is superior in reproducing the spatial pattern of a true map (Dungan et al., 1994; Curran and Atkinson, 1998). None of the spatial statistics employed to date in remote sensing, however, address the problem of spatial registration errors.

The use of local statistics compared with global statistics is outlined by Fotheringham et al. (2002). Local statistics highlight differences occurring spatially in a remotely sensed image, whereas global statistics highlight the similarities. Global statistics by nature are single-valued and are therefore unmappable in a GIS context. However, local statistics measure a given attribute at a particular location, and as the location changes, present a different value. This means that local statistics are suitable for mapping in a GIS environment.

When conducting a quantitative remote sensing study it is necessary to determine the applicability of available spectral regions (location and bandwidth)
for the application. When quantifying biophysical parameters using deterministic or empirical approaches, the information contained in one spectral bandwidth/centre (and polarisation as is the case for polarimetric radar) will vary in comparison to other spectral bandwidths/centres because each react differently with target objects on the ground. For example, in biomass estimation for woody forests, P-HV (P Band with Horizontal transmit and Vertical receive polarisation) displays a higher correlation than L-HH or P-HH (Israelsson et al., 1994; Rauste et al., 1994; Hoekman and Quinones, 1998). Atkinson and Emery (1999) state that spatial variation in a remotely sensed image can differ both in amount and scale between wavelengths. It is this spatial variation that is crucial when field sampling.

Existing literature indicates that the results obtained from analysis of a spatial statistic applied to image data sets (such as the semi-variogram) are dependent on the bandwidth/centre examined (Ramstein and Raffy, 1989; Atkinson and Curran, 1997; Menges et al., 2001). Specifically, Chavez (1992) determined from statistical and visual analyses that the near-infrared band contains more spatial variability than the visible green band, particularly when examining densely vegetated areas. Investigations of optimal resolution have focused on determining the scale at which certain image and environmental parameters are maximized, e.g. between target variance and within target homogeneity (Marceau et al., 1994a,b; Atkinson and Curran, 1997; Phinn et al., 2000; Atkinson et al., 2000; Menges et al., 2001). These studies indicate that the optimal spatial resolution differs between cover types. The spatial statistic implemented in this study locally determines the optimum field sampling size to minimise errors associated with a registration between image and field data. This concept is similar to the definition of an optimal resolution at a local level by determining the minimum support required for linking image to ground data. As images of different resolution are dominated by different geographical or physical features of the surface targets, the optimum sample size is likely to be dependent on ground characteristics as well as image resolution.
2.3. THE NEED FOR QUANTITATIVE MEASUREMENTS OF MELALEUCA BIOMASS IN THE WET/DRY TROPICS

The ability to estimate biomass of woody vegetation as a quantitative environmental parameter is an important component in establishing a natural resource management framework for wet/dry tropical wetland environments from local to national and global scales. A relatively accurate assessment of biomass is particularly valuable for the carbon accounting process, particularly carbon sequestration (Eamus *et al.*, 2000) and is also useful for quantifying changes in landscape structure and processes over time.

However, there are obstacles in quantifying woody biomass in wet/dry tropical wetlands. Wet/dry tropical floodplains are characterised by their remoteness, inaccessibility and strong seasonal variation, thus field surveys are logistically difficult and expensive. Due to the physical properties of these ecosystems, remote sensing provides wetland managers with one of the only effective tools for assessing large-scale management objectives (Phinn *et al.*, 1999). Yet, it is well documented that the use of optical remote sensing technologies is limited to predominantly cloud- and smoke-free acquisition times. More importantly, optical data is unlikely to be able to provide an accurate measure of woody biomass due to its reduced sensitivity at the high biomass levels characteristic of tropical wetlands and forests. It should also be noted that other data processing approaches for estimating tree height and density (i.e. geometric optical models) will not work in the forested tropical wetland environment. On the other hand, SAR is capable of penetrating cloud cover, is not affected by smoke and haze and is sensitive to structure and biomass up to >200 t/ha. For these reasons, SAR data is a suitable alternative (Pope *et al.*, 1994; Rignot *et al.*, 1994; Foody *et al.*, 1997; Yanasse *et al.*, 1997; Santos *et al.*, 2002).

For the scenario of *Melaleuca* expansion in the Trans Fly Bioregion, the remote sensing of newly developing *Melaleuca* forests has an important role in examining not only the region’s carbon balance, but in assessing the impact on habitat heterogeneity (and thus species conservation) and the effect on the natural resources of the indigenous people. *Melaleuca* encroachment (Chapter 1.1.2) due
to disturbance will influence the region’s carbon stocks, accumulating carbon rapidly in their early stages, offset by losses in carbon due to seasonal fire, then gaining carbon slowly once again through regrowth (Luckman et al., 1997). The Trans Fly Bioregion is a difficult area in which to utilise remote sensing technology. Obtaining cloud-free optical images such as Landsat Thematic Mapper (TM) is extremely difficult, and those that are cloud-free are often subject to large active wildfires or ubiquitous atmospheric haze as a result of these fires. Therefore, SAR data offers a more appropriate choice for examining the structure of the *Melaleuca* habitats in this particular region.

### 2.4. BIOMASS ESTIMATION FROM REMOTELY SENSED IMAGERY

Many studies have investigated the use of remotely sensed data for estimating measures of tropical forest biomass. The remotely sensed data used includes optical satellite data such as NOAA AVHRR (Advanced Very High Resolution Radiometer), Landsat TM and large footprint Lidar (Light Detection and Ranging) and active remotely sensed data such as SAR. Each of these data sources has their own advantages and limitations when applied in tropical forest environments as shown by Table 2.1. Regression of biophysical variables and remotely sensed data is an issue to be noted as recognised by Cohen et al. (2003). This issue will be discussed in more detail in Chapter 7.
<table>
<thead>
<tr>
<th>Data Source</th>
<th>Advantages</th>
<th>Limitations</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Satellite</td>
<td>• Can examine forests from the local to regional to global scale  &lt;br&gt; • Availability of cloud and haze free images for tropical regions  &lt;br&gt; • Frequency: too infrequent to capture suitable imagery  &lt;br&gt; • Low sun angle will impact analysis  &lt;br&gt; • Relating red and NIR data to measures of leaf biomass  &lt;br&gt; • Coarse spatial resolution: estimating coverage of forest within a pixel.  &lt;br&gt; • Contribution of understorey green biomass  &lt;br&gt; • Saturation reported at 150 t/ha</td>
<td>Foody and Curran (1994)  &lt;br&gt; Sader et al. (1989)  &lt;br&gt; Steininger (2000)  &lt;br&gt; Nelson et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Lidar</td>
<td>• Not as limited as other technologies in terms of saturation (saturation point in excess of 1300 t/ha)</td>
<td>• Limited acquisition due to cloud and haze (particularly if space borne)  &lt;br&gt; • Not widely available.  &lt;br&gt; • Difficulties arise with understorey flooding</td>
<td>Drake et al. (2002 a, b)  &lt;br&gt; Nelson et al. (1997)</td>
</tr>
<tr>
<td>SAR</td>
<td>• Penetrates cloud cover  &lt;br&gt; • Independent of smoke and haze  &lt;br&gt; • Saturation point is reported as high as 560 t/ha in the P-Band  &lt;br&gt; • L-Band satellites enable regional and potentially global analysis  &lt;br&gt; • P-Band which is most suitable, is restricted to airborne sensors  &lt;br&gt; • Currently, no quad-polarised L-Band satellite sensor available  &lt;br&gt; • Results vary and are site specific</td>
<td>Pope et al. (1994)  &lt;br&gt; Foody et al. (1997)  &lt;br&gt; Luckman et al. (1997)  &lt;br&gt; Yanasse et al. (1997)  &lt;br&gt; Hoekman and Quinones (1998)  &lt;br&gt; Santos et al. (2002)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of remotely sensed data sources for the estimation of tropical forest biomass.
2.4.1. Measuring tropical forest biomass using optical remotely sensed data

2.4.1.1. The use of Spectral Vegetation Indices (SVI) for estimating vegetation biophysical parameters

Studies utilising optical satellite data, commonly use SVIs and in particular the red and near-infrared wavelengths (as the NDVI) in an attempt to estimate or directly model forest structure (height, Diameter at Breast Height (DBH), Leaf Area Index (LAI) and density) (Curran and Atkinson, 1999; Franklin, 2001) and biomass (Sader et al., 1989; Foody and Curran, 1994). The major limitations in implementing SVIs for estimating vegetation biophysical parameters are well documented. Heute et al. (1999) summarise the limitations of optical spectral vegetation indices. External limitations are resultant from: calibration and instrument characteristics; clouds and cloud shadow; atmospheric effects; and sun-target-sensor geometric configurations. Limitations due to canopy characteristics include: canopy background contamination from targets such as soil and surface wetness; and saturation effects whereby SVI values remain unchanged irrespective of amount, type and condition of vegetation. The authors outline further limitations specific to the use of SVIs to derive biophysical vegetation parameters: canopy structural effects derived from leaf angle distributions and clumping and non-photosynthetically active components; and the non-linearity of SVI relationships with specific parameters.

Foody and Curran (1994) report that factors affecting their AVHRR NDVI results for West Africa were topography, haze and issues related to co-locating ground data with the remotely sensed data. Furthermore, these factors in addition to the leafless upper canopy of some of the forests resulted in no relationship between the ground and the Landsat MSS image data. Although the leafless canopy in this study is the result of the forests being semi-deciduous, this raises an important point for the Melaleuca forests, as if a high intensity fire scorches the canopy, they too will be leafless. Sader et al. (1989) demonstrate poor correlations for the relationship between Landsat TM NDVI and total dry weight biomass for tropical mixed broadleaf forest and warn against using the
NDVI to predict total biomass and carbon storage in wet tropical forests. In some studies forest age classes are used as a surrogate for standing biomass, however, this method also cannot be used reliably to estimate biomass from optical satellite data (Nelson et al., 2000). Steininger (2000) found the middle-infrared channel was well correlated with biomass in test sites from Brazil, however when this was applied to forest stands with lower biomass in Bolivia there was no relationship. This highlights the site dependency of successful biomass estimation using optical satellite data. Season and solar zenith angle have been shown to affect the relation between woody canopy cover and red reflectance in savanna (Yang and Prince, 1997), demonstrating that these factors also need to be taken into account. Unlike studies for temperate forests and plantations (Tiwari, 1994; Baulies and Pons, 1995) where relations between biomass and optical data are strong, the results for the tropical forest studies are inconclusive and riddled with caveats. Kasischke et al. (1997) notes that the results from optical investigations show that there is a saturation effect at very low levels of biomass, which is problematic for tropical forest studies where biomass levels are typically high.

Some of the problems with using SVIs as discussed above may be addressed through the use of geometric-optical models in estimating forest structure. Geometric-optical models are a type of spectral model, where the bi-directional reflectance distribution function (BRDF) is modelled as a geometric phenomenon (Scarth et al., 2002). A commonly used model used to improve estimates of biophysical parameters such as LAI is the Li-Strahler geometric optical mutual shadowing (GOMS) forest reflectance model (Li and Strahler, 1992). The improvement to estimates of biophysical parameters is due to the calculation by the model of sub-pixel mixtures of canopy cover, background and shadow components (Peddle, 1999). Another commonly used model is the geometric-optical radiative-transfer (GORT) model (Li et al., 1995) which is relatively complex. The GORT model addresses the three-dimensional geometry of forest canopies and includes multiple scattering between and within tree crowns. However, Hardy et al. (2004) state that the model requires many parameters that are difficult to measure in the field (such as crown geometry and foliage area volume density). Scarth et al. (2002) developed a geometric optical
model that can be applied to the canopy gap structure found in tropical rainforests as opposed to applying a model to individual canopy components. The use of geometric-optical models in estimating biomass is limited to leaf biomass from the canopy and would not be suitable for the flooded tropical floodplain environments where the *Melaleuca* forests investigated in this thesis occur. In addition, many factors including sensor precision, atmospheric effects and BRDF influence the overall accuracy of this semi-empirical approach (Friedl *et al.*, 2001)

2.4.1.2. **Lidar**

In terms of optical sensors, Lidar data shows promise for measuring the biomass of tropical forests, particularly in light of plans to launch the space borne Vegetation Canopy Lidar (VCL) mission in the near future. Lidar is able to measure forest parameters such as stand height (Wulder and Seemann, 2003), foliage projected cover (FPC) (Weller *et al.*, 2003), tree crown diameter (Popescu *et al.*, 2003), leaf area index (LAI) (Lovell *et al.*, 2003) and volume and biomass estimations (Drake *et al.*, 2002a, b; Popescu *et al.*, 2003), by recording the round-trip time for a pulse of laser energy (typically a near-infrared wavelength for forest investigations) to travel between sensor and target. During this time-frame the pulse interacts with forest elements such as the canopy. Strong correlations between forest biomass and lidar data have been demonstrated for wet tropical forest in Costa Rica with a saturation level of approximately 1300 t/ha (Drake *et al.*, 2002a, b). However, an earlier study in the same area in Costa Rica, showed that in two out of three ground data sets the airborne laser significantly underestimated or overestimated ground-measured biomass (Nelson *et al.*, 1997). This shows that further research is needed in linking ground data to the remotely sensed data in more test sites throughout the tropics before the technology is proven. The use of lidar and other optical data in flooded tropical forests (such as the inundated *Melaleuca* forests in the project study areas) is limited due to understorey flooding.
2.4.2. Measuring tropical forest biomass using Synthetic Aperture Radar (SAR)

A body of work exists, reviewing the use of imaging radars for ecological applications (see Bergen and Dobson, 1999; Kasischke et al., 1997; Waring et al., 1995; Ustin et al., 1991). A review and assessment of forestry applications using imaging radar are presented by Leckie and Ranson (1998). The utility of imaging radar for biomass estimation features prominently in these reviews. A component of these reviews presents the basic principles of microwave interactions with forests and vegetation in general and will be summarised herein.

Total backscatter received by a SAR sensor for a forested landscape is composed of numerous backscatter elements as described by Leckie and Ranson (1998) and Kasischke et al. (1997) and is diagrammatically summarised by Figure 2.1. Backscatter elements include:

1. Surface and volume scattering from the crown (e.g.: branches and leaves/needles);
2. Direct trunk scattering;
3. Direct ground scattering;
4. Ground-to-trunk (or trunk-to-ground) scattering also known as double bounce;
5. Crown-to-ground (or ground-to-crown) scattering; and

Backscatter magnitude for the above-mentioned scattering elements is not only a function of canopy elements, but is also dependent on wavelength, incidence angle and polarisation. The interactions of different wavelengths with forest parameters are summarised by Leckie and Ranson (1998), Kasischke et al. (1997) and Waring et al. (1995). Short wavelengths predominantly interact with foliage. K-band (approximately 1 cm) interacts with leaves, X-band (approximately 3 cm) with leaves, twigs and small branches, and C-band (approximately 5.6 cm) with leaves and small and secondary branches. The intermediate L-band interacts with stems, large branches, and trunks and there may be some ground interaction. The longer wavelengths such as P-band
(approximately 68 cm) interact with large branches, trunks and the ground. It must be noted that crown-ground and trunk ground interactions are important at L-band and P-band. The incidence angle influences the difference between HH and VV backscatter and different angles will expose different elements of the forest.

![Figure 2.1: Backscatter elements within a forest: 1) surface and volume scattering from the crown, 2) direct trunk scattering, 3) direct ground scattering, 4) crown-to-ground (ground-to-crown) scattering, and 5) trunk-to-ground (ground-to-trunk) scattering (Source: Leckie and Ranson (1998:464)).](image)

The dielectric properties of a material (such as canopy foliage) are a key parameter that influences the reflectivity and penetration of microwaves related to a material. The relative complex dielectric constant describes the electrical properties of a medium and is composed of a real ($\varepsilon'$) and imaginary ($\varepsilon''$) part. For example, the dielectric constant for dry vegetation material is low ($\varepsilon'$ of <5) whilst the dielectric constant for free water in vegetation is comparatively high ($\varepsilon'$ 60-80) (Leckie and Ranson, 1998; Ustin et al., 1991). Due to their high
moisture content, the individual parts of a tree (trunk, branch, leaves, etc.) constitute discrete scattering and attenuating elements in relation to the transmitted microwaves of imaging radar. However, it should be noted that the dielectric constant can vary for a given vegetative element. Leckie and Ranson (1998) provide an example of this for a tree trunk, whereby the dielectric constant for the outer bark is low, but the phloem and thin vascular cambium layer has a high dielectric constant due to the high moisture content. Reflection due to such a situation is referred to as *volume scattering* and is commonly used to describe backscatter from a vegetation canopy. Another form of scattering is *surface scattering*, determined by the roughness and orientation, which affect the direction and amount of backscatter. This is of particular relevance to the backscatter from the ground below forest canopies, when the wavelength penetrates to the ground or is subject to multiple scattering between the canopy and the ground. Other mechanisms that determine scattering properties in forests include size, shape and orientation of canopy elements. These mechanisms are determinants in the backscatter magnitude.

Despite a relatively large body of work examining the relationship between imaging radar data and above-ground woody biomass, there is still no agreement on the utility of imaging radar in estimating woody biomass. Some researchers believe the saturation level for biomass in radar images is relatively low, whilst others suggest that single-frequency/polarisation saturation levels can be addressed using multichannel images or multistep approaches (Kasischke *et al.*, 1997).
<table>
<thead>
<tr>
<th>Study Site</th>
<th>Limit (t/ha)</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landes Forest, Bordeaux, France (Plantations of maritime pine (Pinus) pinaster)</td>
<td>L-band: 60 – 100 t/ha</td>
<td>Dobson  \textit{et al.} (1992)</td>
</tr>
<tr>
<td>Duke University Research Forest, Durham, North Carolina (Even-aged stands of loblolly pine (Pinus) taeda)</td>
<td>P-band: 100 - 200 t/ha</td>
<td></td>
</tr>
<tr>
<td>Tapajos region, Brazilian Amazon (Clear-cut, regenerating and mature forest)</td>
<td>L-band: 60 t/ha</td>
<td>Luckman  \textit{et al.} (1997)</td>
</tr>
<tr>
<td>Oregon transect Ecosystem Research (OTTER) (Sites ranging from dense coastal forests to slopes of the Cascade Mountains)</td>
<td>P-band: 200 t/ha</td>
<td>Moghaddam  \textit{et al.} (1994)</td>
</tr>
<tr>
<td>International Paper’s Northern Experiment Forest (NEF), Howland, Maine (Boreal, northern hardwood transitional forest consisting of aspen-birch, hemlock-spruce-fir, and hemlock-hardwood mixtures)</td>
<td>AirSAR and SIR-C: 150 t/ha</td>
<td>Ranson and Sun (1997)</td>
</tr>
<tr>
<td>Mucajai, Roraima State, Brazilian Amazonia (Contact zone between savanna and tropical forest)</td>
<td>L-band: 60 t/ha</td>
<td>Santos  \textit{et al.} (2002)</td>
</tr>
<tr>
<td>Guaviare, Columbian Amazon (Primary and secondary forest, and pasture)</td>
<td>L-HV: 52 t/ha</td>
<td>Hoekman and Quinones (1998)</td>
</tr>
<tr>
<td>Araracuara, Columbian Amazon (Flooded and non-flooded forest)</td>
<td>P-HV: 560 t/ha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-band: 100 t/ha</td>
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\textit{Table 2.2: Comparison of SAR saturation points in correlating backscatter intensity with biomass for various forest types.}
The majority of studies examining the relationship between SAR backscatter and tropical forest biomass have been focussed on issues of deforestation and secondary forest regrowth in Central and South America (Pope et al., 1994; Foody et al., 1997; Luckman et al., 1997; Yanasse et al., 1997; Hoekman and Quinones, 1998; Santos et al., 2002), as opposed to woody vegetation encroachment. There is a large body of literature examining the relationship between SAR backscatter and total above ground forest biomass for sites located in Europe (Baker et al., 1994; Beaudoin et al., 1994; Israelsson et al., 1994; Rauste et al., 1994) and North America (Richards et al., 1987; Dobson et al., 1992; Lang et al., 1994; Moghaddam et al., 1994; Rignot et al., 1994; Wang et al., 1995; Harrell et al., 1997; Ranson and Sun 1997; Ranson et al., 1997; Bergen and Dobson, 1999; Chipman et al., 2000) where forest structure differs significantly to that of tropical forests. Luckman et al. (1997) suggest that differences in results between coniferous and tropical forests are due to canopy morphology and structure.

The results of these studies show that the relationship between radar backscatter and biomass varies according to wavelength and polarisation, and the sensitivity of backscatter saturates after a certain biomass level is reached (Kasischke et al., 1997; Yanasse et al., 1997; Bergen and Dobson, 1999). Additionally, the literature highlights that relationships are generally site and community specific with no universal algorithm existent. The lower frequency wavelengths (P- and L- band) are most appropriate for estimation of biomass. Hoekman and Quinones (1998), found that the P-band was suitable in estimating biomass in the range of 10-200 t/ha for tropical secondary regrowth. It has been clearly demonstrated that cross-polarised (HV) backscatter is more sensitive to changes in biomass than backscatter from co-polarised channels (Luckman et al., 1997; Yanasse et al., 1997). Foody et al. (1997) report that no significant relationship existed for the individual channels of SIR-C data when estimating biomass in the range of 63-141 t/ha. However, they found the strength of the relationships increased through the use of backscatter ratios (in this instance LHV/CHV) and by stratifying the forests by dominant species. Saturation levels for biomass vary between sites, however it is agreed that the saturation point is higher for longer wavelengths. For two sites within the one study, the P-HV
channel saturation point was 560 t/ha and 100 t/ha (Hoekman and Quinones, 1998). The use of backscatter ratios may overcome saturation levels to some extent, by reducing the effect of differences due to forest type (Foody et al., 1997). Saturation levels for L- and P-band vary between 40-60 t/ha and 100-560 t/ha respectively for tropical forest studies (Foody et al., 1997; Luckman et al., 1997; Hoekman and Quinones, 1998; Santos et al., 2002).

Few studies have been recorded in the literature relating radar backscatter to forest biomass in the tropical regions of North Australia and there are no studies recorded for New Guinea. Two studies have been conducted in the Northern Territory, Australia, examining the relationship between SAR backscatter and the structural characteristics of *Melaleuca* forests (Menges, 2000; Imhoff et al., 1997). Menges (2000) investigated the relationship between SAR data and biomass and LAI for three vegetation communities at Gunn Point (*Eucalypt* woodland, *Eucalypt* open forest and *Melaleuca* forest). There were weak correlations for *Melaleuca* biomass and SAR backscatter, which was attributed to the heterogeneity of the environment and uncertainty in the spatial location of plots. Another reason for the weak correlation may be that an allometric equation that is not specific to *Melaleuca* was used. *Melaleuca* forest LAI was more strongly correlated with SAR backscatter than biomass, particularly for the C-Band and P-HH. The strong correlation for P-HH was attributed to a strong relationship between Diameter at Breast Height (DBH) and Leaf Area Index (LAI). This study emphasises the need to account for locational uncertainty and variability in backscatter over relatively small areas. Imhoff et al. (1997) conducted a study in Kakadu National Park examining the relationship between vegetation structure and SAR backscatter with reference to *Melaleuca* communities. Contrary to the literature, the L-VV and P-VV channels were highly correlated with the branch and bole (respectively) surface area to volume ratio at the boundary between *Melaleuca* woodland and *Eucalypt* woodland. Additionally the HH backscatter for all bands showed low $R^2$ values for structural components. These results were attributed to the high incidence angle of the data.
3. STUDY SITES

3.1. MARY FLOODPLAIN SYSTEM

3.1.1. Location and Extent

The Mary Floodplain System is located on the coast 75 kilometres east of Darwin, the capital of the Northern Territory, Australia (Coordinates 12°39′ – 12°55′S and 131°31′ - 131°55′E). The site lies between the Adelaide River Floodplain to the north-west and the Camor Plain (east of Point Stuart) to the east and encompasses approximately 127 600 hectares. Figure 3.1 presents a locality map of the Mary Floodplain System. The Mary River catchment occupies approximately 8 500 km² with the river itself originating 80-120 kms from the coast, in the foothills of the Arnhem Land Plateau.

3.1.2. Climate

Like most of northern Australia, the Mary Floodplain System is dominated by a monsoonal climate, with mean daily maximum air temperatures exceeding 30° C throughout the year. The region is characterised by a distinctive wet and dry season. The average annual rainfall is 1 306 mm (Lynch, 1996) with most of this occurring during the four month wet season from December to March. The dry season extends from June to August and is a prolonged period of minimal to nil rainfall and low humidity. April-May and September-November are transitional months dominated by wet-dry and dry-wet weather respectively (Taylor and Tulloch, 1985). Wet season rainfall varies between years and within wet seasons (Lynch, 1996).
Figure 3.1: Location of the Mary Floodplain System
3.1.3. Significance

The Mary Floodplain System is listed in “A Directory of Important Wetlands in Australia” (Usback and James, 1993). The criteria for inclusion as recorded in the Directory are:

- It is a good example of a wetland type occurring within a biogeographic region in Australia.
- It is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
- It is a wetland which is important as the habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought, prevail.
- The wetland supports 1% or more of the national populations of any native plant or animal taxa.
- The wetland is of outstanding historical or cultural significance.

Table 3.1 lists the wetland types present in the study area as recorded by the Directory also.

Of particular interest in regards to this thesis, is that the site contains the second largest stand of wooded swamp (*Melaleuca* sp.) in the Northern Territory (Whitehead and Chatto, 1996), and perhaps one of the largest stands in Australia. The Mary River Conservation Reserve located in the western part of the site protects this habitat. The wetlands are unusually diverse and productive, with their complex mosaic of habitats supporting an array of fauna (Whitehead, 1999). This may be attributed to the fact that the drainage rate is lower than other neighbouring systems and that the seasonal wetlands are inundated even in times of comparatively low rainfall, thereby providing suitable habitats for longer periods of time (Whitehead and Chatto, 1996). The floodplains contain some of the most extensive *Hymenachne* and *Pseudoraphis spinescens* communities in the Top End (Whitehead and Chatto, 1996). An area within the Mary Floodplain System, centred on Shady Camp Billabong, has been included on the Register of the National Estate as a “reported place: insufficient data to evaluate”.

50
Table 3.1: Wetland types of the Mary Floodplain System (after Usback and James, 1993).

<table>
<thead>
<tr>
<th>MARINE AND COASTAL ZONE WETLANDS</th>
<th>INLAND WETLANDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Estuarine waters; permanent waters of estuaries and estuarine systems of deltas.</td>
<td>• Permanent rivers and streams; includes waterfalls.</td>
</tr>
<tr>
<td>• Intertidal mud, sand or salt flats.</td>
<td>• Seasonal and irregular rivers and streams.</td>
</tr>
<tr>
<td>• Intertidal forested wetlands; includes mangrove swamps, nipa swamps, tidal freshwater swamp forests.</td>
<td>• Riverine floodplains; includes river flats, flooded river basins, seasonally flooded grassland, savanna and palm savanna.</td>
</tr>
<tr>
<td></td>
<td>• Seasonal/intermittent freshwater ponds and marshes on inorganic soils; includes sloughs, potholes; seasonally flooded meadows, sedge marshes.</td>
</tr>
<tr>
<td></td>
<td>• Freshwater swamp forest; seasonally flooded forest, wooded swamps; on inorganic soils.</td>
</tr>
</tbody>
</table>

3.1.4. Vegetation

The flora of the Top End floodplains is cosmopolitan, and floristically and structurally simple yet spatially complex (Whitehead et al., 1990). These Top End wetlands form heterogeneous mosaics of vegetation with floristic composition changing from year to year due to seasonal differences, such as timing, duration and intensity of the wet season (Cowie et al., 2000). Determinants in floodplain vegetation patterning are water depth, which is associated with micro topography (Whitehead et al., 1990), climatic controls such as rainfall and the timing of flooding, salinity gradients, and position of the water table (Bowman and Wilson, 1986). Cowie et al. (2000) state that the distribution of *Melaleuca* trees varies between floodplains and the fact that some floodplains like that of the Mary River support large forests can not be attributed to differences in geomorphology. However, the authors suggest that within a
floodplain system the distribution of *Melaleuca* species is controlled by salinity
tolerance and the pattern of flooding.

The vegetation of the Mary Floodplain System has been mapped and
described in recent times by Whitehead *et al.* (1990) at 1:250 000 scale and by
Lynch (1996) at 1:50 000 scale. Additionally the *Melaleuca* communities have
been mapped (National Forest Inventory in the Bureau of Rural Sciences, 1993)
for the National Forest Inventory. Lynch (1996) describes 47 communities that
are derived from the elevation and morphological provinces described by
Woodroffe and Mulrennan (1993) and other vegetation surveys. 9 of these 47
communities are dominated by species of *Melaleuca* and of these 9 communities,
2 are units that are regenerating *Melaleuca* which were once subject to salt water
intrusion. The dominant species are *Melaleuca cajuputi*, *Melaleuca viridiflora*
and *Melaleuca leucadendra*, occurring as closed or open forests and woodlands.
The understorey species differ amongst these *Melaleuca* communities.

General trends in floodplain vegetation on the Mary Floodplain System are
summarized as follows:

- Whitehead *et al.* (1990) report that the reed *Phragmites karka* is not
  present, however there is a higher proportion of *Melaleuca* and
  *Hymenachne* communities occurring compared with adjacent floodplains
  (Wilson *et al.*, 1990; Lynch, 1996). Although no reason is suggested for
  the absence of *Phragmites karka*, the higher proportion of the other
  communities is related to the presence of extensive low-lying areas that
  remain inundated for more than 5 months (Lynch, 1996).

- Mangroves and samphire plains (grasslands) dominate saline and semi
  saline communities. Common mangrove species inhabiting the littoral
  fringe and displaying zonation (from the seaward to the landward zone)
  are *Sonneratia alba*, *Avicennia marina*, *Rhizophora stylosa*, and *Ceriops*
  *tagal*. Dominant species of the samphire communities include *Sporobolus
  virginicus*, *Xerochloa imberbis*, *Schoenoplectus litoralis* and *Paspalidium
distans*. 
Sedgelands and mixed herb/grass/sedge communities characterise what Cowie et al. (2000) term the ‘dry freshwater community groups’. These communities only become inundated at the peak of the wet season and are the first areas to dry out. The sedgelands are dominated by *Cyperus scariosus* and *Eleocharis dulcis*. Other species that exist in the mixed communities include *Pseudoraphis spinescens*, *Panicum sp.*, *Fimbristylis spp.*, *Merremia gemmella*, *Malachra fasciata*, *Oryza rufipogon* and *Phyla nodiflora*.

Floating mats grasslands/sedgelands and paperbark forests and woodlands dominated the ‘wet freshwater community groups’. These habitats remain inundated for at least a few months of the dry season and are generally the wettest part of the floodplain (Cowie et al., 2000). Floating mats located within billabongs are composed of *Leersia hexandra*, *Hymenachne acutigluma*, *Ludwigia adscensdens* and *Ipomea aquatica*. Grasslands/sedgelands contain *Oryza rufipogon* and *Eleocharis sphacelata*. Paperbark forests and woodlands are characterised by *Melaleuca cajuputi*, *M. leucadendra* and *M. viridiflora*. The understorey of these habitats is composed of a mixture of the above mentioned grasses, sedges and aquatics.

Fringing communities are those that are adjacent to the floodplain on elevated ground. These communities are mixed woodlands dominated by *Eucalyptus* species and grasses from the genus *Heteropogon*.

### 3.1.5. Geomorphology

The wetland system is defined by Whitehead and Chatto (1996) as being a mega scale irregular floodplain composed of numerous billabongs and creeks, several tidal creeks, a mesoscale irregular river (in the southern part of the site) and intertidal mudflats up to 1 km wide. Cheniers (beach ridges) up to 2m in height run parallel to the coastline and former buffalo swim-channels are evident throughout the floodplain. The mudflats, saline coastal flats and estuaries are
tidal and are generally inundated twice daily, however, parts of the saline coastal flat may only be inundated after deluge events such as floods and storm surges.

Woodroffe and Mulrennan (1993) have published a comprehensive study on the geomorphology of the Lower Mary River Plains. Three morphological provinces and associated units have been defined and are summarized as follows:

**Coastal Plain:**

The coastal plain is a progradational landform that has developed due to near shore marine processes resulting in the deposition of sediments in Chambers Bay. The elevational range is between 0.6m AHD (for the mangrove morphological unit) up to 3.1m AHD (for levees in the eastern part of the site) and it is approximately 16kms wide (Cowie, et al., 2000). AHD is Australian Height Datum, which is sea level. This province is divided from the paleoestuarine plain by a chenier that represents the shoreline 6000 years ago. Morphological units found on the coastal plain include mangrove, saline mudflat, lower and upper coastal plain, levee, paleochannel, paleocreek and chenier. The unit defined as the *Lower coastal plain with Melaleuca* is similar in geomorphological terms to the lower coastal plain and is distinguished due to the occurrence of *Melaleuca*. Elevation is generally less than 2.0m AHD, however the authors state that this unit had not been surveyed extensively due to inaccessibility (these areas remain inundated for most of the year). The Mary River Conservation Reserve is located within this unit.

**Paleoestuarine Plain:**

This province formed as a tidal floodplain flanking and estuarine channel, and has an elevational range of 2.5-2.6m AHD near Shady Camp to 3.0-3.2m AHD near Corroboree billabong (Applegate, 1994). The morphological units of this province (like those of the coastal plain) are differentiated by elevation and frequency of inundation. These units are the upper floodplain, lower floodplain, lower floodplain with *Melaleuca*, backwater swamp, lower backwater swamp, paleochannel and levee. The lower floodplain with *Melaleuca* unit is defined by relatively low-lying areas at some distance from main channels. These areas remain inundated into the dry season and support *Melaleuca* woodland. Similarly
the higher ground (which is dry only for a couple of months) within the backwater swamp unit, supports *Melaleuca*.

**Alluvial plain:**

The alluvial plain was not described in great detail by Woodroffe and Mulrennan (1993) as it occurred outside their area of study. This province is located to the south of the paleoestuarine plain and is characterised by alluvial sediments. The average elevation of the alluvial plain is significantly greater than that of the other provinces and is in excess of 4.5m AHD.

Woodroffe and Mulrennan (1993) report on the evolution of the freshwater wetlands of the Lower Mary River plains as evidenced by drilling, pollen analysis and radiocarbon dating. The Lower Mary River plains are Holocene in age and were dominated by different phases during this 10 000 year time period. The *transgressive phase* began 7 000 years ago and was marked by a widespread mangrove forest that continued to expand landwards with the sea level rise. At around 6 000 years ago as the sea level stabilized, the *big swamp phase* began. During this time, *Rhizophora*-dominated mangrove forests extended south of Shady Camp. The freshwater wetlands are young and started developing 4 000 years ago as coastal progradation accelerated. These environments became extensive 2 000 years ago (Whitehead *et al.*, 1990).

**3.1.6 Fauna**

The Mary Floodplain system is a major dry season refuge for Saltwater Crocodile (*Crocodylus porosus*) and waterbirds with at least 75 species of waterbirds recorded in the area. At least 11 species of these waterbird are reported as breeding in the site. In addition it is a key breeding area (and one of the most important in Australia) for Magpie Goose (*Anseranas semipalmata*), and has the highest breeding concentration of the White-bellied Sea-eagle (*Haliaeetus leucogaster*) in the Northern Territory. The coastal flats are an important migration stop-over for thousands of migrant shorebirds (Whitehead and Chatto, 1996).
Saltwater Crocodile are found in high numbers in the Shady Camp Billabong. The wetlands are an important fishery, particularly for the somewhat iconic Barramundi (*Lates calcarifer*) and attract many amateur fishermen for this reason. Over half of the recreational Barramundi fishing occurring in the Northern Territory is on the Mary Floodplain System (Julius, 1994). Griffin (1994) states that the Barramundi generates a substantial amount of economic activity in the region and that the Mary River Wetlands are key to sustaining this situation.

### 3.1.7. Environmental Threats

Whitehead *et al.* (1990) outline some of the environmental threats to the wetlands of the Mary Floodplain System. The foremost threat is saltwater intrusion, which has accelerated since the 1950s. The Mary Floodplain System is the worst affected floodplain in the Top End (Whitehead and Chatto, 1996). The cause of this phenomenon (which also occurs in the Alligator Rivers Region of Kakadu National Park) is the subject of debate. Some believe it is attributed to high densities of feral water buffalo, while others believe it is a natural process in these low-lying coastal environments. Over the last 50 years the Mary River changed its morphology from a series of disconnected billabongs (as opposed to a continuous channel to the sea) to having an outlet that exists as a 3km channel from Shady Camp billabong to Cambers Bay (Applegate, 1994). The tidal creek systems of both Tommycut and Sampan Creeks has expanded considerably since the 1940s and now have extensive dendritic networks associated with them that are penetrating into the freshwater environments (Woodroffe and Mulrennan, 1993). As a result large areas of paperbark forest and freshwater grasses and sedges have died as shown by Figure 3.2. The process of tidal creek expansion is expected to continue (Woodroffe and Mulrennan, 1993).

Other threats include the invasion of the exotic weed *Mimosa pigra* (Giant Sensitive Plant) which has become well established since the 1980s and will continue to spread, and the presence of feral animals (Whitehead *et al.*, 1990).
1990). Feral water buffalo were previously exceeding densities of 20km\(^2\) and were associated with adverse impacts on vegetation. This density has since been reduced to 1km\(^2\). Feral pigs (*Sus scrofa*) on the floodplains are of concern and impact severely on floodplain vegetation.

![Figure 3.2: Melaleuca forest that has been subject to saline intrusion in the north-west of the Mary Floodplain System (Photo: G.Hill).](image)

**3.1.8. Management**

The Northern Territory Government has adopted a multiple land use strategy for the Mary Floodplain System that integrates the conservation and economic objectives of multiple stakeholders. A large portion of the western part of the area is under a cattle-grazing lease with some pastoral activities also taking place in the eastern region. Pastoralism accounts for 25% of the landuse in the floodplains (Ferdinand et al., 2001). The pastoral leases are located at Marrakai, Woolner, Opium Creek, Melaleuca and Swim Creek. The conservation areas are under the jurisdiction and management of the Northern Territory Department of Infrastructure Planning and Environment (DIPE). These conservation areas include the Mary River Conservation Reserve (27 000 ha), which protects the
large stand of paperbarks in the northwest and several smaller sites. The Mary River Landcare Group is the stakeholder responsible for Landcare for the area and integrates their activities with the pastoralists.

In response to the saline intrusion issue DIPE and some pastoralists have been actively building earthen barrages to protect the freshwater environments. Major barrage construction was undertaken at Shady Camp in 1988 and ongoing barrage construction in the north-western area of the floodplains has been conducted. This has resulted in the regeneration of *Melaleuca* that had previously died as shown by Figure 3.3.

![Figure 3.3: Regenerating Melaleuca forest that had been subject to saline intrusion in the north-west of the Mary Floodplain System.](image)
3.2. TRANS FLY BIOREGION: WASUR NATIONAL PARK AND TONDA WILDLIFE MANAGEMENT AREA

3.2.1. Location and Extent

Wasur National Park (Taman Nasional Wasur) and Tonda Wildlife Management Area (TWMA) are situated in the biologically rich Trans-Fly Bioregion of southern New Guinea. “New Guinea” refers to the whole island of which the independent Papua New Guinea and the Indonesian province of West Papua (Irian Jaya) are political entities. The Trans-Fly Bioregion extends from the Digul (Digoel) River in the west to the Fly River in the east and encompasses the land to the south of these rivers. The area of interest in this study is the South New Guinea savannas which cover in total approximately 2.5 million hectares of the Trans-Fly Bioregion (Chatterton, 2000). The study area (refer to Figure 3.4) spans the international border, which is marked by the mouth of the Torassi River (also known as the Bensbach River). Access to this region (particularly Tonda) is quite difficult due to its extreme remoteness and lack of transport infrastructure.

Wasur National Park (WNP) is located in the far south-east corner of the Indonesian Province of West Papua (Irian Jaya) and is bounded by the international border with Papua New Guinea, the coast and the Maro River (also known as the Merauke River) (Coordinates 08°39’S and 140°48’E). The National Park also incorporates Rawu Biru Reserve. Originally, an area of 308,000 hectares was declared a National Park by the Ministry of Forestry in 1990, followed by a total area of 413,810 hectares being gazetted in 1997. Of this area, the wetlands cover 263,200 hectares. The only Indonesian town located in this region of West Papua is Merauke, situated a few kilometres from the south-west boundary of Wasur NP. A Transmigration Highway running from Merauke to Tanah Merah bisects the National Park. This highway has facilitated access to the park.

Tonda WMA is located in the far south-west corner of Papua New Guinea in the Western province and is bounded by the international border with
West Papua, the coast, extending 50 kms inland and the Mai Kussa River in the east (Coordinates 08°45’S and 141°23’E). In 1975, the PNG Department of Environment and Conservation (DEC) established Tonda WMA in collaboration with the local communities, thus incorporating 590,000 hectares into the conservation area. There are two administrative centres for the Western Province, Morehead and Balumuk District headquarters located just north of Tonda WMA. The closest major town is the coastal town of Daru situated 200 kilometres to the east of Tonda WMA.

Collectively, Wasur NP and Tonda WMA conserve over 1 million hectares of tropical wetland and savanna habitat within the Trans-Fly Bioregion.

### 3.2.2. Climate

The climate of the Trans-Fly region is monsoonal defined by a wet season extending from December to May and a dry season extending from June to November. In general terms this is the driest ecoregion in New Guinea with 1500 to 2000 mm annual rainfall (Chatterton, 2000). Specifically, average annual rainfall for the region as reported in 1971 was 1875mm with the majority of this (75%) falling during the wet season (Paijmans et al., 1971c). The flat topography and impeded drainage combine to ensure that widespread flooding follows highly seasonal rainfall. There is a rainfall gradient present in the region distinguished by higher rainfall in the slightly elevated northern plateau area compared with the lowlands. This gradient is associated with a decrease in rainfall seasonality (McAlpine, 1971; Barano and Ridarso, 1998). Mean annual rainfall also appears to increase from the west to the east of the region (McAlpine, 1971).

Local people suggest that the rainfall during the wet season has declined in the last decade. This was substantiated by Barano and Ridarso (1998) who had analysed rainfall records collected since 1952 from three rainfall stations in the Wasur.
Figure 3.4: Location and context of Wasur National Park and Tonda Wildlife Management Area
Mean annual temperature for the region in 1971 was 26.6°C. The mean dry season temperature represented by the month of July is 25.5°C and the mean wet season temperature represented by the month of December is 27.7°C. Mean annual humidity for the region is approximately 85% (McAlpine, 1971).

The following is a summary of the six seasons recognized by the Kanum (indigenous people) and what these seasons are marked by (Wasur National Park-Visitor Guide):

1. *Teuratoro tanggal tbra* (October-November)
   This period is the top season of hot weather when parts of the swamps start drying out. It is during this season that the forests and woodlands are burnt. Animals seek shelter in the swamps and rivers where water still remains.

2. *Nananggal* (December-January)
   This is the beginning of the rainy season.

3. *Umper* (February-March)
   Umper marks the middle of the rainy season when the swamps are full of water and the animals have sought refuge in the uplands.

4. *Muli* (April-May)
   The west wind rain distinguishes this season. Trees are knocked down during thunderstorms.

5. *Nanggai Wetar* (June-July)
   It is during this time that rainfall decreases and the rainfall that does occur is bought by the east winds. The swamps start to drain and the grasses start to dry out and become yellow.

6. *Tebrataro* (August-September)
   This period of the year is the transition season where the mornings and evenings are cool, and the swamps begin to dry out. This also signals the beginning of the fire season.
3.2.3. Significance

New Guinea is the world’s largest tropical island and is nearly always associated with rugged terrain and impenetrable jungles. However, the Trans-Fly Region is dominated by monsoonal savannas providing a unique and diverse habitat for many species. The faunal and floristic assemblage that is characteristic of the region can be attributed to the existence of a land bridge between Australia and New Guinea during the last glacial period.

The Trans-Fly landscape is unique for many reasons. It is morphologically mostly open and flat compared with the mountainous areas of central New Guinea. The flora and fauna resemble that of neighbouring northern Australia. The area’s wetlands are amongst some of the most pristine, diverse and extensive in the world. Of particular interest from a biodiversity perspective are extensive tracts of grassland, which are not represented elsewhere in Indonesia or Papua New Guinea. These grasslands, distributed as they are on the coastal plains and river flood plains, are particularly prone to seasonal inundation. When inundated, the grasslands are the favoured habitat of a diversity of waders and waterfowl, many of which migrate to and from northern Australia. For example, the total global population of the Little Curlew (Numenius minutus) passes through the Trans-Fly coastal plains on its migration between Australia and Siberia. Including the Little Curlew, 15 species of what are termed small northern hemisphere migratory birds prefer or are restricted to the intertidal zone of Wasur and Tonda (Stronach, 1998a).

The region supports the most distinct regional avifauna in New Guinea and is consequently listed as an Endemic Bird Area by Birdlife International (Bowe, in press). A conservative estimate of 335 bird species has been recorded in Wasur alone. Five of these species are endemic to the Trans-Fly region and are poorly understood in relation to their distribution and threats (Stronach, 1998a). The endemic bird species include the Fly River Grass Warbler (Megalurus albolimbatus), Little Paradise Kingfisher (Alcedo pusilla), two species of Lonchura including the Grey-crowned Munnia (Lonchura nevermanni) and the Spangled Kookaburra (Dacelo tyro). In 1991 World Wild Fund for Nature
(WWF) became involved in conservation activities in Wasur due to its importance in terms of Palaearctic Waders (Bowe, 1998). Arerr, in Wasur, is a key waterbird nesting habitat as shown in Figure 3.5 and also accommodates a large Flying Fox roosting colony.

Figure 3.5: The waterbird nesting habitat at Arerr, Wasur National Park.

As mentioned previously, both Wasur and Tonda were declared conservation areas in the form of a National Park and Wildlife Management Area in 1990 and 1975 respectively. Tonda is PNG’s oldest and largest conservation reserve and became the country’s first Ramsar site designated in 1993 (Bowe, in press). Wasur has been nominated to become Indonesia’s fourth Ramsar site. The Park’s Ramsar nomination stems from the fact that the wetlands and savanna support large concentrations of waterfowl and migratory palaearctic waders.

The wetland types recorded for Tonda WMA under the conservation reserve’s Ramsar listing (according to Ramsar defined categories) are summarised below in descending order of dominance. These wetland types also occur in Wasur.
• **Seasonal/intermittent freshwater marshes/pools** on inorganic soils; includes sloughs, potholes, seasonally flooded meadows, sedge marshes.

• **Freshwater, tree-dominated wetlands**; includes freshwater swamp forests, seasonally flooded forests, wooded swamps on inorganic soils.

• **Permanent freshwater marshes/pools**; ponds (below 8ha), marshes and swamps on inorganic soils; with emergent vegetation water-logged for at least most of the growing season.

• **Intertidal forested wetlands**; includes mangrove swamps, nipah swamps and tidal freshwater swamp forests.

• **Permanent rivers/streams/creeks**; includes waterfalls.

• **Seasonal/intermittent/irregular rivers/streams/creeks**.

• **Seasonal/intermittent freshwater lakes** (over 8 ha); includes floodplain lakes.

• **Sand, shingle or pebble shores**; includes sand bars, spits and sandy islets; includes dune systems and humid dune slacks.

In 1995 the concept of the Tri-National Wetlands program was established by WWF. The program facilitates collaboration between land managers in Wasur, Tonda and Kakadu National Park (Northern Australia), to overcome management issues such as feral animals and weed control. Additional to undertaking joint training and research, the program aims at sharing information on different systems of community based natural resource management (Bowe, in press).

### 3.2.4. People

Wasur NP and Tonda WMA are relatively sparsely populated with an average density of approximately 0.6 persons per square kilometre (Chatterton, 2000). This is attributed to the harsh conditions, which are characterised by a shortage of drinking water during the dry season and widespread flooding during the wet season (Paijmans, 1971a). A historical factor that may have also contributed to this situation may have been depopulation arising from the head-
hunting practices of the Tugeri who raided the tribes inhabiting the region east of the Torasi River, prior to the Dutch administration (Paijmans, 1971a).

New Guinea is recognised as having the highest linguistic diversity on earth, represented by over 1000 languages. Within the Trans-Fly coastal zone there are 14 languages and over 25 dialects (which include from west to east: Kanum, Marind, Marori, Yei, Tonda, Rouku/Nambu, Peremka, Suki, Pahatouri, Mutum, Bine, Gizra, Gidra and Kiwai). The Trans-Fly people are typified by their use of paperbark in their building and by what are believed to be agricultural prehistoric mounds (Chatterton, 2000).

Four indigenous groups live within the boundaries of Wasur NP for whom the park is their traditional land. These are the Marind, Yei, Marori-Mengey, and Kanum peoples, inhabiting 12 villages in total. In 1990, there were 2000 indigenous people living in the park (Bowe, 1997). Today there are some 3000 inhabitants (Chatterton, 2000). The indigenous people have been recognised by the government as an asset to WNP and have been permitted to live within the park, with the aim of integrating them into the planning and management process (Bowe, 1997). There are between 1 000-1 500 people living in Tonda WMA (Chatterton, 2000). These people inhabit 28 villages situated throughout the WMA (Bowe, in press). Tonda WMA is managed by a committee composed entirely of representatives from the major language groups.

The people of this area are largely subsistence farmers with the regional economy based predominantly around yam cultivation and augmented with hunting and gathering of forest products. The Kanum people are primarily yam cultivators whilst the Marind, Yei and Marori-Mengey are mostly sago cultivators (Chatterton, 2000; Bowe, in press). The people of Tonda are primarily yam gardeners. Within both conservation reserves there are tourism ventures. In Tonda there is a tourism operation running out of the Bensbach Lodge, which was the area’s main economic activity until land conflicts in recent years impacted on its operation (Chatterton, 2000; Bowe, in press). Local villages are eager to trade in wildlife and forest products. For example, people in Tonda trade deer antlers at Sota in West Papua.
3.2.5. Vegetation

The vegetation of New Guinea on the whole remains inadequately known as some regions are yet to be surveyed. This is particularly true for the international border area of the Trans-Fly Region (Paijmans, 1990). The study area is characterised by the southern vegetation region defined by Paijmans (1971b). *Melaleuca* trees represented by a number of species dominate this southern vegetation region. The key determinants in vegetation patterning (as is the case for most wetland environments) are climate, topography and drainage (Paijmans, 1971b). Climate refers to the timing of the wet season and the amount of rainfall; topography determines the inundation regime, whereby small differences in elevation in this habitat dictate the distribution of vegetation types; and drainage, which also determines the inundation regime. The seasonality, specifically prolonged inundation followed by dry conditions has resulted in vegetation communities that are relatively poor in floristics and structure (Paijmans, 1971b).

The origin of the vegetation within the study area is not entirely clear with some elements that are of Malaysian origin and others of Australian origin (van Royen, 1963; Paijmans, 1971c). Paijmans (1971b) states that the vegetation is similar both floristically and especially physiognomically to that found in northern Australia. Some of the examples include the *Melaleuca viridiflora* savanna, *Melaleuca* swamp forest and *Tristania-Grevillea-Banksia* community. Van Balgooy (1976:18) states that “the savanna element in New Guinea is doubtlessly young…” The perception that the majority of the grasses, herbs and shrubs are Australian elements is not proven from the current knowledge obtained from surveys (Paijmans, 1971b). A relatively small proportion of species (within the framework of current surveys) are entirely common to the study area and northern Australia, with various species of *Melaleuca* amongst them. It is suggested that these species have migrated northwards from Australia (van Royen, 1963; Paijmans, 1971b). Swadling and Hope (1992) estimate that the savanna encroached upon the rainforest areas around 25 000 years B.P. With the rise in sea level, the rainforest expanded to its present distribution by 12 000 years B.P. The further northward advancement of Australian species has been
hampered by the dense rainforest of Malaysian origin, which has contributed to
the southward movement of Malaysian species into the study area (Paijmans,
1971c). Van Royen (1963) raises the interesting scenario that under a drier
climate the vegetation of Wasur and Tonda may be able to advance into the
rainforest community and thereby represents a preclimax.

Paijmans (1971b) distinguished 25 vegetation types in the Morehead-
Kiunga Area, PNG. The major environments for the occurrence of these
vegetation types in the study area are categorized by Paijmans (1976) as: Beach
ridges and flats; Saline and brackish swamps; Lowland fresh water swamps; and
Lowland alluvial plains and flats. The following is a summary of the vegetation
types defined by Paijmans (1971b, 1976) occurring within the study area.

**Beach ridges and flats**

This environment is not the focus of this thesis, therefore is discussed
briefly. Vegetation types present are: Herbaceous beach vegetation; Beach scrub;
Beach woodland; *Casuarina* forest; and mixed littoral forest. Herbaceous
communities dominate the beachward zone whilst tall forests are characteristic of
the landward zone. Swamp vegetation is located in the swales between beach
ridges.

**Littoral Forest (Mixed Littoral Forest):**

Littoral forest is commonly located on the inland beach ridges and on
some flats. The forest is composed of mixed species including *Melaleuca
cajaputi, Ficus, Syzygium* spp. and *Acacia auriculiformis*. Palms such as
*Corypha* are common in the midstorey. This habitat is often subject to seasonal
inundation.

**Saline and brackish swamps**

Again, this environment is not the focus of this thesis, therefore is
discussed briefly. Vegetation types present are: Mangrove scrub; Low mangrove
forest; Mature mangrove forest; *Avicennia* scrub and woodland; *Excoecaria*
scrub and woodland; *Sporobalus* grassland; and Nipah palm woodland.
Mangroves and other salt-tolerant species dominate this environment due to the tidal influence.

**Lowland fresh water swamps**

Vegetation patterning in the lowland freshwater swamps is determined by inundation regimes, topography and associated water depth and water quality. Deep water environments are colonized by communities of free-floating aquatics, whilst shallow water zones are inhabited by rooting water plants. Swamp grasses dominant those areas subject to moving water and colonise both deep and shallow flooded zones of the alluvial plains. In the shallower swamps, trees and shrubs form savanna/woodland/forest communities. Swamp forests are tallest in the permanent swamps behind river levees that display strong fluctuations in water levels and are at times well drained and aerated. In the back swamps the swamp forest is usually less dense, thinner-stemmed and lower in height.

**Aquatic vegetation:**

This community is composed of free-floating and semi-submerged aquatics such as *Azolla imbricata, Pistia stratiotes*, lilies of the genera *Nymphaea* and *Nymphoides* and the lotus *Nelumbo nucifera* as shown in Figure 3.6. These aquatics form either mosaics or mono-specific colonies.

**Low swamp grassland (Pseudoraphis grass swamp):**

This habitat is reported by Paijmans (1971b) to be located on the floodplains of the Torasi, Tarl and Wanggoe Rivers and is also distributed in the transition zones between permanent swamp and higher ground inhabited by *Melaleuca*. This habitat is also well-represented in Wasur as shown by Figure 3.7. As a result this habitat is inundated for the majority of the year. This vegetation type is typically characterised by pure dense mats of *Pseudoraphis spinescens* (water couch grass). These mats form the most extensive representations of this habitat in New Guinea and give the landscape a parkland appearance. When the ground dries out, deer and wallabies heavily graze these mats. Other grasses, which may be present but not in the same density are *Setaria* sp. and *Digitaria* sp. Sedges such as *Fimbristylis* spp. are common. In terms of
trees, there are sparsely scattered low trees consisting of *Barringtonia tetraptera*, *Dillenia alata*, *Nauclea orientalis*, *Melaleuca cajaputi* and *M. viridiflora*.

![Figure 3.6: Open swamp dominated by Lotus (*Nelumbo nucifera*) in Wasur National Park.](image)

**Figure 3.6:** Open swamp dominated by Lotus (*Nelumbo nucifera*) in Wasur National Park.

![Figure 3.7: Pseudoraphis grass swamp with Nauclea orientalis in Wasur National Park.](image)

**Figure 3.7:** *Pseudoraphis* grass swamp with *Nauclea orientalis* in Wasur National Park.
Mid-height Swamp Grassland (*Leersia* grass swamp):

This community dominated by floating grasses inhabits permanently swampy areas of the floodplains that can be inundated to 3 metres during the wet season. The grasses form ‘islands’ that often come adrift from their anchoring and float downstream sometimes making it to the ocean. The floating grass mats play an important part in the hydrology of these wetlands. These swamp grasses are represented by *Oryza rufipogon* (wild rice), *Leersia hexandra* (rice grass) and *Hymenachne acutigluma*. *Hanguana malayana* is sometimes present in these mats. Large pure stands of *Hanguana malayana* flank Rawu Biru. In less deep water that periodically dries out, *Ischaemum polystachyum* dominates the community, which in this case is also composed of *Oryza rufipogon*, *Leersia hexandra*, *Eleocharis dulcis* and *Phragmites karka*.

Mid-height Grassland (*Imperata* grassland):

The *Imperata cylindrica* (kunai, also known as *alang alang*) grasslands occur on low-lying seasonally inundated beach plains where they form pure and dense stands. These grasslands are an important habitat for the people in the area as they are good hunting grounds for deer and wallabies and are thus maintained by burning. This is a habitat in decline in the study area. Open patches form in the grassland where the grass has been trampled and killed by deer. Paijmans (1971b:94) states that “numerous *Melaleuca* seedlings occur locally in these open patches but they will not survive the next fire”. Recent field trips indicate that these *Melaleuca* seedlings in open patches are surviving fire and becoming established. There may have been a change in the traditional use of fire by people since the Paijmans survey which has contributed to this phenomenon. Trees in this habitat are distributed sparsely and include *Melaleuca cajuputi*, *Alstonia actinophylla* and *Livistona* palm. Figure 3.8 depicts typical *Imperata* grassland in Wasur that is now subject to weed invasion.
Tall Swamp Grassland (*Saccharum-Phragmites* grass swamp):

This vegetation type is composed of the tall grasses *Saccharum robustum*, *Phragmites karka* and *Coix lacryma-jobi* and either forms pure stands or mosaics depending on the frequency and duration of flooding. *Phragmites* is the tallest of the three tall grass species (up to 5 metres) and dominates the back swamps and edge habitats of open water. It tolerates a wide range of conditions, growing in both permanent swamps and seasonally dry sites, in brackish or freshwater environs and can grow under dense tree canopy. In recent decades there has been a dramatic decline in *Phragmites* in this area. Most grasses shoot from an intercalary meristem, however *Phragmites* shoots from an apical meristem. As a result, *Phragmites* does not respond well to grazing by wallabies and deer. However, wallaby are not the more robust grazer of the two as they do not wade out so far into inundated areas as deer. When *Phragmites* is subject to fire, shooting will occur from the rhizomes. Therefore, the decline in stands of *Phragmites* may be attributed to extensive grazing by introduced deer. A healthy stand is dense and composed of individuals that are tall and thick-stemmed. For example, a 1m$^2$ plot can yield 73 stems with an average thickness of 1.5-2 cm and average height of 2.5-3m. These stands are no longer common. Although not quantified or proven, they play an important role in wetland hydrology by reducing the velocity of water flow and retaining water in localized areas for
longer periods of time. Figure 3.9 depicts the edge of a Phragmites swamp on the coastal plain of the Yausem River, Wasur.

![Image](image_url)

**Figure 3.9: Edge of the Phragmites swamp at the Yausem River in Wasur National Park.**

**Tall Sedge-Grass Swamp Vegetation:**

This habitat is characterised by permanent swamp with shallow standing water. Broad-leaved sedges such as Scleria poaeformis and Thoracostachyum sumatranum dominate the swamp, with Melaleuca and Acacia shrubs occurring on hummocks. *Phragmites karka* is common along the swamp margins with *Pseudoraphis spinescens* and *Ischaemum polystachyum* forming an edge habitat on the wet-dry margins. Stands of *Scleria poaeformis* have been in decline for reasons not known. This vegetation is a crucial nesting habitat for the Fly River Warbler (*Megalurus albolimbatus*). Figure 2.10 shows a relict *Scleria* habitat at Yauram, Wasur.
Figure 3.10: Relict Scleria open swamp at Yauram, Wasur National Park.

*Melaleuca* Swamp Savanna:

Within the study area there are occurrences of *Melaleuca* swamp savanna on low-lying flats that are inundated to a considerable depth during the wet season. This habitat is more common and extensive in the back swamps of the middle Fly and Strickland Rivers. The vegetation is dominated by a homogenous even-age stand of thin-stemmed *Melaleuca*. The stands are characterized by low and crooked trees that vary in height and stem morphology. The Kanum people recognize this and have various names for the same species of *Melaleuca* based on their growth form. The two most common species of *Melaleuca* present in this habitat are *M.cajuputi* and *M.leucadenda* however stands of this swamp savanna are normally dominated by one species. Low swamp grasses and sedges dominate the understorey. In the late dry season fire burns these habitats and can be of such intensity that a crown fire occurs thereby defoliating the trees.

*Melaleuca* Swamp Forest:

This vegetation type is almost exclusively confined to the study area (in relation to New Guinea) and is unusual in terms of tropical forests due to its monotypic floristic structure. The distribution of these forests appears to be controlled by rainfall. Where annual rainfall is greater than 2500 mm, *Melaleuca* swamps do not exist, and in areas of annual rainfall between 2000-2500 mm *Melaleuca* is represented by a few scattered trees amongst a mixed swamp forest
(Paijmans, 1990). In the study area, where mean annual rainfall is less than 2000 mm, the forests consist of predominantly *Melaleuca cajaputi* although other *Melaleuca* species are sometimes present or take the dominant role. The average canopy height is 30 metres and canopy closure rarely exceeds 50% as the crowns are small in comparison to overall tree size as shown by Figure 3.11. Other tree species present include *Dillenia alata*, *Nauclea orientalis* and *Acacia* spp. Generally there is no shrub layer and the understorey is sparse. Sedges and grasses such as *Pseudoraphis* are present in the more poorly drained sites. In forests that contain permanently inundated areas, aquatic vegetation is present. These forests when dry are subject to annual fire.

![Figure 3.11: Melaleuca Swamp Forest in Wasur National Park.](image)

**Lowland Alluvial Plains and Fans**

Paijmans (1976), states that the monsoonal plains of the study area are unique in terms of the forests and woodlands present. The lowland plains are dominated by dry forest, woodland and savanna that are similar to those of
northern Australia. Five of the eight vegetation types described by Paijmans (1976) for the lowland alluvial plains are restricted to the study area.

Schoenus-Eriachne Sedge-Grassland:

This habitat is a feature of the poorly drained plains that are completely dry during the dry season and are inundated during the wet season due to the heavy clay soils they are situated on. The sedge Schoenus spp. (Figure 3.12) is either dominant or is equivalent to the proportion of grasses present including Ischaemum barbatum and Eriachne spp. and usually form tussocks interspersed with annual grasses and algae. In the dry season the algae dries out forming a crust. Termite mounds (also known as termitaria) are a prominent feature of this community. Further inland these sedge-grasslands form a complex mosaic with dry evergreen forest and savanna. This patterning is determined primarily by micro topography and edaphic conditions.

Figure 3.12: Schoenus sedgeland during the wet season near Witer, Wasur National Park.

Melaleuca Savanna:

The Melaleuca savannas of the Trans-Fly Region are virtually identical to those of northern Australia (particularly Kakadu National Park). This habitat is located on low-lying flats bordering the coastal plain and is inundated during the
wet season. The dominant species is *Melaleuca viridiflora* forming pure stands of gnarled and thin-stemmed trees, however in areas such as Witer (Wasur NP) *Asteromyrtes symphyocarpa* co-dominates (as shown in Figure 3.13). The Kanum people have names for *Melaleuca* based on their growth form. For example the gnarly crooked trees are called “wariru” and are signified as such because “they can’t grow straight”. Both the Kanum and Marori people have names for the sub species based on distinguishing between the colours of blossoms. The ground cover is composed of the sedge *Schoenus* spp. and grasses such as *Ischaemum barbatum* and *Germainia capitata*.

![Asteromyrtes symphyocarpa at Witer, Wasur National Park.](image)

**Figure 3.13: Asteromyrtes symphyocarpa at Witer, Wasur National Park.**

**Low Mixed Savanna:**

This vegetation type is associated with poorly drained flats with the habitat structure influenced by the frequency of fire and drainage characteristics. The dominant trees include *Asteromyrtes symphyocarpa*, *Grevillea glauca*, *Banksia dentata* and *Tristania suaveolens*. Other species that may be present are *Melaleuca viridiflora*, *Eucalyptus polycarpa* and *Dillenia alata*. A shrub layer is usually present. The ground cover is composed of sedges such as *Schoenus* spp.
and grasses such as Imperata cylindrica. During the wet season the low mixed savannas are inundated and are burnt during the dry season.

**Tall Mixed Savanna:**
Tall mixed savanna is commonly located on the well-drained and gently undulating terrain in the northern parts of the study area that are not inundated during the wet season. This habitat replaces dry evergreen forest when it is repeatedly damaged by frequent fire. The vegetation is similar to low mixed savanna except that larger trees in terms of both height and girth are present, and the shrub layer is also taller. The most common trees are Melaleuca cajaputi and Tristania suaveolens. Other trees present include Melaleuca leucodendra, Asteromyrtes symphyocarpa and Acacia mangium.

**Monsoon Forest (Dry Evergreen Forest):**
The Monsoon Forests are located on gently undulating well-drained plains. Villages in the southern part of the study area are often located in the monsoon forests and associated patches of bamboo. This habitat contains all the species found in the Tall Mixed Savannas and a few representatives of the rainforest as shown in Figure 3.14. The canopy is approximately 25 metres high and the dominant trees are Acacia spp., Syzygium spp., Tristania, Magnifera, Halifordia and occasionally Melaleuca spp. The shrub layer is not dense enough to prevent entry on foot and is composed of palms and bamboo. Where the forest canopy is open, patches of bamboo woodland occur. These forests are prone to fire, which kills the fire-sensitive trees and shrubs. If the forest is repeatedly damaged by fire it is likely to be converted to savanna.

**Sinoga Scrub:**
This habitat is susceptible to fire and is composed entirely of Sinoga lysicephala. It normally occurs in the Schoenus-Eriachne mosaic described previously. It can form quite dense stands usually 1-1.5 metres high.
3.2.6. Geomorphology

The land resources of the Morehead-Kiunga area (Papua New Guinea, in which Tonda is located) have been extensively surveyed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia (Paijmans et al., 1971). Table 3.2 summarises the land systems found within Tonda. This survey also summarises the land resources of the area that is now Wasur. The study area has been divided into two geographic regions: the coastal plain; and the Oriomo Plateau (also known as the Merauke Ridge).

Coastal Plain

The coastal plain is defined by low beach ridges, flats and swales in the coastal zone, and a back plain extending further inland. Numerous tidal creeks and medium-sized rivers dissect the plain, draining water from the wetlands during the wet season. The area is inundated by freshwater during the wet season.
due to the dominance of poorly drained marine clays. Areas of permanent swamp are limited. The coastal plain is situated approximately 5 metres above sea level. The ridges and flats are dominated by *Imperata* grassland and littoral forest, with the tidal flats supporting mangroves. The back plain is predominantly characterised by low sedge-grassland, with reeds and tall sedges dominating the permanent swamps. The seasonal swamps support *Melaleuca* swamp forest, whilst the higher ground supports *Melaleuca* savanna and *Imperata* grassland (Paijmans, 1971b). This plain is dominated by recent sediments and aggradational land forms (Blake, 1971).

Blake (1971) describes the fluvial geomorphology of the area. Considerably sinuous meandering channels bordered by narrow floodplains define the Torasi and Morehead Rivers whilst the Tarl River is much less sinuous in nature. Permanently swampy paleochannels associated with the Morehead and Tarl Rivers are evident in this geographic region. During the dry season the coastal back plain is characterized by a complex pattern of reticulate to dendritic narrow drainage channels.

**Oriomo Plateau**

The Oriomo Plateau abuts the coastal plain on the northern limit and rises to a maximum of 55 metres above sea level where it is bounded by the valley of the Fly River. It is characterised by gentle undulations and becomes seasonally inundated in low-lying areas with the onset of the wet season. Relatively small rivers are present that are associated with narrow floodplains. The area abutting the coastal plain is dominated by *Melaleuca* savanna on poorly drained soils, with the undulated country characterised by monsoon forest and tall mixed savanna (Paijmans, 1971c). This plateau is dominated by denundational land forms (Blake, 1971).

The Morehead, Torasi and Wanggoe Rivers flow from the main watershed of the plateau. Streams within this geographic entity are typically widely spaced, associated with narrow floodplains and flow in open V-shaped valleys generally not exceeding a depth of 10 metres. Deposition of sediment
occurs on the floodplains, the small streams are often influenced by down-cutting and there is lateral erosion of stream banks brought about by meander migration (Blake, 1971).

<table>
<thead>
<tr>
<th>Land system</th>
<th>Geology</th>
<th>Main Land Forms</th>
<th>Altitude (a.s.l) (metres)</th>
<th>Relief (metres)</th>
<th>Predominant soil</th>
<th>Predominate Vegetation</th>
<th>Drainage</th>
<th>Flooding and Inundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal plain</td>
<td>Wunji</td>
<td>Littoral sand, silt, and clay</td>
<td>Non-tidal and tidal flats; low beach ridges and swales</td>
<td>0-1.5</td>
<td>&lt;1.5</td>
<td>Weakly acid to neutral over alkaline marine clay</td>
<td>Littoral forest and woodland</td>
<td>Largely very poorly drained</td>
</tr>
<tr>
<td>Bula</td>
<td>Clay and silt</td>
<td>Plain</td>
<td>0.6-6</td>
<td>&lt;1.5</td>
<td>Strongly gleyed alluvial clay, weakly acid over alkaline or acid over weakly acid</td>
<td>Sedge-grassland</td>
<td>Poorly to very poorly drained</td>
<td>Largely inundated in wet season</td>
</tr>
<tr>
<td>Wando</td>
<td>Alluvial clay and silt</td>
<td>Swampy floodplain</td>
<td>0.6-9</td>
<td>&lt;3</td>
<td>Organic soils, and strongly gleyed alluvial clay, acid to strongly acid</td>
<td>Herbaceous swamp vegetation, <em>Melaleuca</em> swamp forest, low swamp grassland</td>
<td>Swampy to very poorly drained</td>
<td>Permanently inundated or inundated for less than 3 months a year</td>
</tr>
<tr>
<td>Tonda</td>
<td>Alluvial clay and silt</td>
<td>Floodplain</td>
<td>1.5-4.5</td>
<td>&lt;3</td>
<td>Strongly gleyed alluvial clay commonly with a thick dark topsoil, acid to strongly acid</td>
<td><em>Imperata</em> grassland, <em>Melaleuca</em> swamp forest</td>
<td>Poorly drained</td>
<td>Probably flooded and inundated for less than 3 months a year</td>
</tr>
<tr>
<td>Oriomo Plateau</td>
<td>Morehead</td>
<td>Pleistocene clay</td>
<td>Broad shallow valleys</td>
<td>3-27</td>
<td>6-24</td>
<td>Loamy sand to loam overlying mottled clay loam to clay</td>
<td>Sedge-grassland, <em>Melaleuca</em> savanna</td>
<td>Imperfectly drained</td>
</tr>
<tr>
<td>Mibini</td>
<td>Alluvial clay</td>
<td>Smooth plain</td>
<td>1.5-15</td>
<td>&lt;1.5</td>
<td>Loam overlying mottled clay loam to clay, acid to strongly acid</td>
<td><em>Melaleuca</em> savanna</td>
<td>Imperfectly to poorly drained</td>
<td>Large parts inundated in wet season</td>
</tr>
<tr>
<td>Indorodoro</td>
<td>Clay</td>
<td>Gently undulating plain</td>
<td>15-36</td>
<td>9-15</td>
<td>Sandy loam to loam overlying mottled clay loam and clay, acid to strongly acid</td>
<td>Monsoon forest and tall mixed savanna</td>
<td>Well to imperfectly drained</td>
<td>Locally inundated in wet season</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of the characteristics of land systems found within the study area (After Paijmans et al., 1971:20-23).

Van Royen (1963) and Blake (1971) discuss the geomorphic history of Wasur and Tonda respectively. The story for both areas is similar. Unlike most of New Guinea which has been formed from tectonic activity, the Oriomo Plateau has formed part of a comparatively stable shelf since the Jurassic. The landscape of the area is suggested to be the result of gentle warping and
dissection of the Plio-Pleistocene piedmont alluvial plain and sea level changes in the last 27 000 years. The region was subject to the global marine transgression that began 17 000 years ago and ceased about 6 000 years ago. Figure 3.15 illustrates the development of the coastal plain. During the marine transgression phase, the lower courses of the Tarl, Torasi and Morehead Rivers and associated area were inundated. When the sea level reached its present limit a few thousand years ago, the coastline of the initial stage was represented by northern extent of the present coastal plain. The intermediate stage is defined by the deposition of beach ridges from the Morehead River across to the Merauke region, as a result of long shore drift from the mouth of the Fly River. As a result, an extensive lagoon formed which was at times isolated from the sea. The present stage is represented by the infilling of the lagoon by fluvial sediments from the major rivers, thereby creating the present day coastal back plain. At the same time, the Tarl River diverted its course to flow down the Torasi River, and likewise the Morehead River developed a new channel to the sea. It is suggested by Blake (1971), the present paleochannel to the east of the Morehead River once separated a small island off the coast. Still clearly visible in the landscape of Wasur, are old coastal walls that run parallel to the coastline of the regression period in which they were deposited (van Royen, 1963). These coastal walls follow a WNW-ESE and give the coastal plain a striking geometric appearance when observed on satellite imagery.

The paleo-environment of Wasur and Tonda can be explained by the existence of a large lake. Carpentaria was the largest lake ever known in Australia and covered the Gulf of Carpentaria and the Torres Strait approximately 36 000-10 000 years ago (Swadling and Hope, 1992). The drainage basin covered the study area prior to the uplift of the Oriomo plateau, with the actual lake situated within the land bridge. The environment in the region at this time would have been dominated by open grassland.

Barano and Ridarso (1998) define three catchment areas in Wasur. They are the Maro, the Ndali and the Torasi (the largest catchment by area). The only permanent open freshwater area is Rawa Biru. In 1998 the authors report that water was being drawn from Rawa Biru for the town of Merauke at a rate of 40
litres/sec\(^{-1}\) during the wet season and 200 litres/sec\(^{-1}\) in the dry season. Projections at that time suggested that Merauke would require 400 litres/sec\(^{-1}\) which would result in the complete draining of the oxbow lagoon in the dry season. It is not clear what measures have been taken to manage this obviously unsustainable water extraction.

![Figure 3.15: Development of the coastal plain in the study area. (a) Initial stage; (b) intermediate stage; (c) present stage (Source: Blake, 1971:63).](image)

### 3.2.7. Fauna

The Trans-Fly displays a high degree of endemism in terms of fauna, which is perhaps the primary impetus for the conservation of the region’s biodiversity. The region is renowned for its avian diversity as discussed previously, and displays high mammalian diversity and endemism with up to 80 species expected (Chatterton, 2000). Some of the endemic mammals include the
carnivorous marsupial Bronze Quoll (*Dasyurus spartacus*), a subspecies of the Red-Legged Pademelon (*Thylogale stigmatica*) and the Chestnut Dunnart (*Sminthopsis archeri*). Three species of bat, the Lesser Tube-nosed Fruit Bat (*Paranyctimene raptor*), *Nyctimene draconilla* and the Broad-Striped Tube-Nosed Bat (*Nyctimene aello*) are listed as rare.

It had been suggested that the False Water-rat (*Xeromys myoides*), which is distributed in northern and eastern Australia, may also have occurred in New Guinea. In 1998, the collection of two specimens from Wando village in Tonda, confirmed this (Hitchcock, 1998). The specimens were found on the edge of an *Eleocharis* swamp. With *Melaleuca* expansion occurring in this area, Hitchcock (1998) states that this change in vegetation has resulted in the reduction of suitable habitat for the False Water-rat.

The Salt Water Crocodile (*Crocodylus porosus*) and New Guinea Freshwater Crocodile (*Crocodylus novaeguineae*) are present, however their numbers have been drastically reduced due to hunting. The Salt Water Crocodiles are now largely restricted to the lower reaches of the Torasi river. In regards to other reptiles, the wetlands are an important breeding area for freshwater turtle species including the little known Fly River or New Guinea Plateless Turtle (*Carettochelys insculpta*). There are six known species of large varanids including the Timor Tree Monitor (*Varanus timorensis*), Blue-Tail Monitor (*Varanus doreanus*) and the Papuan Monitor (*Varanus salvadorii*).

There are many species of fish present in the waterways. There has been 63 species of fish recorded in the Torasi River. Some biological surveys of the Rawa (oxbow lagoons) have been conducted previously in Wasur (Barano and Ridarso, 1998). The Barramundi (*Lates calcarifer*) is relatively abundant as are numerous species of Rainbow Fish. However, Stronach (1998b) relays an account from villagers that about one-third of the fish species in Wasur had disappeared; one-third had reduced in population and one-third had remained unaffected. He has linked this with the introduction of the Climbing Perch (*Anabas testudineus*), which degrades water quality through significantly increasing the turbidity of water. It is also likely the more recent introduction of
the Snakehead Murrel (*Channa striata*) to Wasur, then Tonda has exacerbated species decline. This fish known as “*gasto*” by local people and feeds on fish, insects, frogs, snakes and tadpoles. Additionally it is well adapted to survive the dry season and reductions in water levels. Several other countries report adverse ecological impacts after introduction. Their numbers in the Torasi River appear to have reached plague proportions.

The Rusa Deer (*Cervus timorensis*) were introduced during the Dutch colonial administration at Merauke in 1928, from where they spread to most of the lowland areas in the Trans-Fly region (Bowe, 1997). The initial population introduced to Merauke is believed to be a dozen. Their numbers exploded as they were well adapted to the environment and there are no natural predators present (Bowe, 1997). There is an estimated population of 60 000 in the Tonda region at present (Frazier, 1999). Stronach (1998b) recounts that aerial surveys during 1992-1994 indicated that there were 12 000 deer present in the Wasur grasslands, however suggests that this may have been an overestimate. He estimates that 90% of deer in Wasur were killed, 1% died of natural causes and 9% died of unknown causes. These figures contradict that of a predicted population of 72 000 deer in Wasur alone from an Indonesian report dated 1986 (Stronach, 1998b) and an estimate of 70 800 in 1988 (Bowe, 1997). The numbers of deer are lower in Wasur due to the trade in Merauke of deer meat and other products, such as antlers. Most of this trade is conducted by hunters from Merauke, evidence that there is a poaching problem in the park. The traditional people are now being encouraged to take part in this trade and throughout the Trans-Fly now hunt deer as a source of protein in their diet (Bowe, in press). It is believed that the deer are a key disturbance agent instigating widespread landscape change throughout Wasur and Tonda.
3.2.8. Environmental Threats

There are numerous threats to the biodiversity of the Trans-Fly region. The most immediate threat comes from exotic weed infestations, which may overcome the seasonally inundated grassland and wetland environs. These weeds include the Giant Sensitive Plant (*Mimosa pigra*), Snakeweeds (*Stachytarpheta* sp.), Siam Weed (*Chromolaena odorata*) and Water Hyacinth (*Eichhornia crassipes*). Their spread across the Trans-Fly region is facilitated by the interconnectedness of the hydrology, the use of motorised transport and the construction of roads.

As part of the Indonesian Government’s Transmigration Program, other large tracts of grasslands in the southern lowlands of West Papua (Irian Jaya), outside WNP have been settled by migrants from overpopulated centres elsewhere in Indonesia (Bowe, in press). These migrants are converting land for agricultural purposes, ultimately reducing the extent of natural grassland in the region.

Introduced or feral animals are directly threatening both native fauna and flora and more holistically the integrity of the landscape. A change in landscape integrity will ultimately impact the fauna and flora not directly affected by predation or competition, due to a reduction in available habitat. Introduced animals within the conservation areas include cattle, horses, dogs, cats and wild pig (Bowe, in press). Additionally, as discussed previously there are introduced fish species that alter water quality and may pose a threat to native fish species. Stronach (1998b) reports that the introduced African Land Snail (*Achatina fulica*) and Golden (Apple) Snail (*Pomacea* sp.) are present within the monsoon forests of Wasur and may easily spread. It is not entirely clear what damage these snails will cause in the environment, however reports on the Golden Snail indicate that it may feed voraciously on young aquatic grasses, as it does on juvenile rice crops elsewhere in Asia.

The grasslands of Wasur and Tonda are at the centre of an alarmingly rapid landscape change. Woody vegetation encroachment is clearly evident when
examining historical aerial photography from the 1940s in comparison with recent satellite imagery. The dominant woody species invading the grasslands is *Melaleuca sp.* The primary disturbance agent in the wetlands is believed to be Rusa Deer (*Cervus timorensis*), which due to their intense grazing in the wetlands has decimated some species of grasses. Where deer are or have in the past been abundant, the tall *Phragmites* swamps have largely disappeared.

The deer are able to graze extensively on swamp grasses due to their ability to move through inundated areas. Anecdotal evidence from the indigenous people suggests the vegetation has changed greatly since the introduction of deer. Stronach (in Bowe, 1997) reports that three major habitat changes have reportedly occurred since the deer have been introduced:

1. A significant reduction in the abundance of tall swamp grasses, in particular floating mats of *Hymenachne*. These floating mats provided an important habitat for waterfowl and crocodiles, and perhaps more importantly controlled the extent of seasonal drying in the wetlands;

2. A rapid decline in the distribution and vigour of *Phragmites karka* stands, which are easily accessed by the deer. The dense *Phragmites* stands would have slowed the drainage of water from the wetlands towards the end of the wet season, thereby prolonging the period of inundation. Since the decline of these stands, the swamps have become less extensive and more seasonal.

3. The most pronounced landscape change is the encroachment of *Melaleuca* sp. onto the grasslands. Inhabitants within the conservation areas report that large expanses of grassland have been converted to *Melaleuca* forest and woodland. *Imperata* grasslands have been significantly reduced by the grazing activities of deer and subsequent impacts of fire. Stronach (1998b) reports that the less palatable *Chrysopogon* replaces these grasslands.

The encroachment of *Melaleuca* into the grassland habitats is of the most concern as it is uncertain whether this landscape change can be reversed. The people living within Wasur and Tonda are dependent on the grasslands as a cultural resource, particularly in relation to hunting pigs and deer. These people
have said that it becomes increasingly difficult to hunt these animals in the Melaleuca woodlands and forest. There is a particular anecdotal account from Wando village in Tonda that illustrates the impact that the spread of Melaleuca has had on people. In recent times a Melaleuca forest has grown up around the back of the village. During the 1997 wildfire this Melaleuca forest caught on fire and due to the oil content of the trees; people report that it started to explode. The villagers ended up swimming across the Torasi River to safety. Not only does this landscape change affect people, it has the potential to alter the Trans-Fly’s biodiversity values.

A combination of feral animal impacts and fire in conjunction with the drying out of swamp habitats is leading to this demise in the area of grassland, which will ultimately result in a reduction in the region's biodiversity. Factors that may also be contributing to a drop in the water table of the wetlands include unsustainable water extraction from Rawa Biru, changes in swamp hydrology due to the removal of grasses and an apparent reduction in wet season rainfall. Simply this change has been induced by the interaction of fire, ferals and flood.

3.2.9. Management

Although essentially the same wetland system, Wasur and Tonda are governed by different management approaches due to the international border. Bowe (in press) has described in detail the differences in management models. The Indonesian Ministry of Forestry’s Directorate of Protection and Nature Conservation (PKA) is responsible for the management of the Wasur National Park, with the indigenous people having a limited role in management and decision-making. In contrast, Tonda WMA is managed by a selected committee of landowners who develop rules specifically related to management, exploitation of wildlife and WMA boundaries. The establishment of the Tri-National Wetlands Program (as discussed previously) further strengthens the management of these conservation areas.
The agency responsible for the management of Wasur National Park is the Minister of Forestry’s Directorate of Protection and Nature Conservation (PKA). A National Park Unit (Balai Taman Nasional) is established at Wasur to manage responsibilities including the development and implementation of a Park Management Plan (Bowe, in press). Within Indonesia, the customary land rights of indigenous people are not clearly stated or recognized in national legislation. However, with successful lobbying from WWF, Wasur became the first park in Indonesia where local peoples’ rights were recognized through the implementation of a “Traditional Use Zone”. This enabled communities to conduct traditional management activities including hunting and gathering (Bowe, in press). The impetus to further include indigenous communities within the park in management continues.

Papua New Guinea has one of the most strongly developed and politically recognised customary land tenure systems in the world with 97% of the country controlled by indigenous people (Chatterton, 2000). The rights of indigenous communities are clearly stated in national legislation (Bowe, in press). Chatterton (2000:5) states that Tonda “…is a fascinating experiment in indigenous management of wetland areas”. The author focuses on the development of formal land management within Tonda and outlines the existing resource management approaches the people had developed. These include a complex system of landscape zoning, areas with entry restriction, areas with activity restrictions, periodic harvesting restrictions, species harvest restrictions, size limits on harvested wildlife and fire control. The Tonda WMA is composed entirely of male landowners. The Office of Environment and Conservation (OEC) is the State agency responsible for providing support to the WMA.
3.3. SUMMARY

This chapter presented an overview of the three study areas that were used in this thesis: The Mary Floodplain System (northern Australia); Wasur National Park (West Papua/Irian Jaya) and Tonda Wildlife Management Area (Papua New Guinea). The later two are essentially treated as the same study area because they are contiguous and in effect represent the same wetland system, located within the Trans-Fly Region of New Guinea. The Trans-Fly sites were discussed in greater detail as these sites are poorly understood in terms of western science, compared with the Mary Floodplain System where a great deal of scientific work has been conducted over the last couple of decades.

There are many similarities between the Mary Floodplain System (and northern Australia in general) and Trans-Fly wetlands. Both have extensive stands of Melaleuca forest that are periodically inundated; are subject to a monsoonal climate dominated by seasonal rainfall; are low-lying (in relation to sea level) coastal ecosystems; remain relatively unmodified; and share many faunal and floral elements. A more controversial similarity is that both wetland complexes have been influenced by introduced herbivore ungulates (Paijmans et al., 1971c). Large numbers of Water Buffalo (Bubalus bubalis) inhabited the Mary Floodplain System in the 1960s-1970s, with some individuals still present today, whereas large herds of Rusa Deer (Cervus timorensis) are present in Wasur and Tonda. However, the study sites differ in terms of natural resource management models. Also the Trans-Fly has extensive areas of seasonally flooded savanna which are somewhat absent from the Mary Floodplain System.

The Mary Floodplain System was chosen as a study site due to the comparatively easy access, thus allowing remote sensing methodologies to be developed. These methods were then “tested” and adopted for the Trans-Fly sites. Additionally these sites can be compared and contrasted in terms of approaches to remote sensing applications.
4. RESEARCH DESIGN AND DATA DESCRIPTION

4.1. RESEARCH DESIGN

The main aim of this thesis is to determine above ground woody biomass of *Melaleuca* on tropical floodplains using remote sensing data.

A two-step methodology was applied in this project. Firstly, the location and size of *Melaleuca* biomass field sample sites was pre-determined for the Mary Floodplain System using a spatial statistic developed during the project. As discussed previously, the accurate linking of ground data with remotely sensed data in regards to spatial error is a key issue in quantitative remote sensing studies. The spatial statistic and subsequent testing are discussed in detail in Chapter 5. The spatial statistic was not applied to the Trans Fly data prior to field sampling due to the timing of field work in those sites in the project cycle. This enabled a comparison of the biomass mapping results obtained with and without the implementation of the spatial statistic. Secondly, remote sensing data sources were assessed for their utility in accurately estimating *Melaleuca* biomass. Once the most suitable data source was established, mapping was conducted.

Data collection involved conducting field sampling of *Melaleuca* biomass in both the Mary Floodplain System and Trans Fly sites. In assessing the spatial statistic, ADAR digital data, Landsat TM, MASTER and TOPSAR data were collected. For the purpose of biomass mapping an investigation of suitable remote sensing data was conducted. Radar data were collected for both sites for this purpose. Ancillary data sources included Landsat TM scenes and previous mapping work conducted on the Mary Floodplain System (Lynch, 1996).
4.2. DESCRIPTION OF DATA

This section presents a description of the data used in this project. The data sources are presented in two sections: the Mary Floodplain System data (4.2.1); and the Trans Fly data (4.2.2).

4.2.1. Mary Floodplain System Data

The extents of the core spatial datasets used for the Mary Floodplain System are illustrated in Figure 4.1. These image data are TOPSAR, MASTER, ADAR and Landsat 7 ETM+. Further detail on these data is provided in the following sections.

4.2.1.1. TOPSAR Data

TOPSAR data is acquired through the JPL (Jet Propulsion Laboratory) AirSAR system. The AirSAR instrument acquires backscatter data at C-band (5.6 cm wavelength, 5.3 Ghz frequency), L-band (23.9 cm wavelength, 1.25 Ghz frequency) and P-band (68 cm wavelength, 0.44 Ghz frequency) in four transmit/receive polarisations (HH, VV, HV, and VH). There are two TOPSAR mixed modes of operation: XTI1 and XTI2. The XTI1 mode produces a C-band Digital Elevation Model (DEM) and L- and P-band polarimetry. In most instances, the XTI2 mode produces a C-band and an L-band DEM, and P-band polarimetry.

The JPL (Jet Propulsion Laboratory) AirSAR system was flown over the study site on board a DC-8, in TOPSAR mode XTI1, on the 15th of September, 2000 (at the end of the dry season), during the NASA PACRIM 2000 mission. TOPSAR acquired topographic height data through C-VV interferometry, and multi-polarised backscatter data at L-band and P-band in. Weather conditions were dry with smoke present from wildfires. Two 10 x 60 km swaths were captured, which covered the majority of the floodplain.
4.2.1.2. MASTER Data

The MASTER instrument (MODIS / ASTER airborne simulator (Hook et al., 2001) records information in 50 spectral bands covering the visible, near-infrared (NIR), mid-infrared (MIR) and thermal infrared (TIR) portions of the electromagnetic spectrum as shown in Table 4.1.
<table>
<thead>
<tr>
<th>Spectral Channel</th>
<th>Band centre (µm)</th>
<th>Bandwidth (µm)</th>
<th>Spectral Range</th>
<th>Spectral Channel</th>
<th>Band centre (µm)</th>
<th>Bandwidth (µm)</th>
<th>Spectral Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.460</td>
<td>0.04</td>
<td>0.440-0.480</td>
<td>26</td>
<td>3.150</td>
<td>0.15</td>
<td>3.075-3.225</td>
</tr>
<tr>
<td>2</td>
<td>0.500</td>
<td>0.04</td>
<td>0.480-0.520</td>
<td>27</td>
<td>3.300</td>
<td>0.15</td>
<td>3.225-3.375</td>
</tr>
<tr>
<td>3</td>
<td>0.540</td>
<td>0.04</td>
<td>0.520-0.560</td>
<td>28</td>
<td>3.450</td>
<td>0.15</td>
<td>3.375-3.525</td>
</tr>
<tr>
<td>4</td>
<td>0.580</td>
<td>0.04</td>
<td>0.560-0.600</td>
<td>29</td>
<td>3.600</td>
<td>0.15</td>
<td>3.525-3.675</td>
</tr>
<tr>
<td>5</td>
<td>0.660</td>
<td>0.06</td>
<td>0.630-0.690</td>
<td>30</td>
<td>3.750</td>
<td>0.15</td>
<td>3.675-3.825</td>
</tr>
<tr>
<td>6</td>
<td>0.710</td>
<td>0.04</td>
<td>0.690-0.730</td>
<td>31</td>
<td>3.900</td>
<td>0.15</td>
<td>3.825-3.975</td>
</tr>
<tr>
<td>7</td>
<td>0.750</td>
<td>0.04</td>
<td>0.730-0.770</td>
<td>32</td>
<td>4.050</td>
<td>0.15</td>
<td>3.975-4.125</td>
</tr>
<tr>
<td>8</td>
<td>0.800</td>
<td>0.04</td>
<td>0.780-0.820</td>
<td>33</td>
<td>4.200</td>
<td>0.15</td>
<td>4.125-4.275</td>
</tr>
<tr>
<td>9</td>
<td>0.865</td>
<td>0.04</td>
<td>0.845-0.885</td>
<td>34</td>
<td>4.375</td>
<td>0.15</td>
<td>4.275-4.425</td>
</tr>
<tr>
<td>10</td>
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<td>0.04</td>
<td>0.885-0.925</td>
<td>35</td>
<td>4.500</td>
<td>0.15</td>
<td>4.425-4.575</td>
</tr>
<tr>
<td>11</td>
<td>0.945</td>
<td>0.04</td>
<td>0.925-0.965</td>
<td>36</td>
<td>4.650</td>
<td>0.15</td>
<td>4.575-4.725</td>
</tr>
<tr>
<td>12</td>
<td>1.625</td>
<td>0.05</td>
<td>1.600-1.650</td>
<td>37</td>
<td>4.800</td>
<td>0.15</td>
<td>4.725-4.875</td>
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<tr>
<td>13</td>
<td>1.675</td>
<td>0.05</td>
<td>1.650-1.700</td>
<td>38</td>
<td>4.950</td>
<td>0.15</td>
<td>4.875-5.025</td>
</tr>
<tr>
<td>14</td>
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<td>0.05</td>
<td>1.700-1.750</td>
<td>39</td>
<td>5.100</td>
<td>0.15</td>
<td>5.025-5.175</td>
</tr>
<tr>
<td>15</td>
<td>1.775</td>
<td>0.05</td>
<td>1.750-1.800</td>
<td>40</td>
<td>5.250</td>
<td>0.15</td>
<td>5.175-5.325</td>
</tr>
<tr>
<td>16</td>
<td>1.825</td>
<td>0.05</td>
<td>1.800-1.850</td>
<td>41</td>
<td>5.400</td>
<td>0.15</td>
<td>5.300-5.450</td>
</tr>
<tr>
<td>17</td>
<td>1.875</td>
<td>0.05</td>
<td>1.850-1.900</td>
<td>42</td>
<td>5.550</td>
<td>0.15</td>
<td>5.400-5.550</td>
</tr>
<tr>
<td>18</td>
<td>1.925</td>
<td>0.05</td>
<td>1.900-1.950</td>
<td>43</td>
<td>5.650</td>
<td>0.15</td>
<td>5.500-5.650</td>
</tr>
<tr>
<td>19</td>
<td>1.975</td>
<td>0.05</td>
<td>1.950-2.000</td>
<td>44</td>
<td>5.750</td>
<td>0.15</td>
<td>5.600-5.750</td>
</tr>
<tr>
<td>20</td>
<td>2.075</td>
<td>0.05</td>
<td>2.050-2.100</td>
<td>45</td>
<td>5.850</td>
<td>0.15</td>
<td>5.750-5.900</td>
</tr>
<tr>
<td>21</td>
<td>2.160</td>
<td>0.05</td>
<td>2.135-2.185</td>
<td>46</td>
<td>5.950</td>
<td>0.15</td>
<td>5.900-6.050</td>
</tr>
<tr>
<td>22</td>
<td>2.210</td>
<td>0.05</td>
<td>2.185-2.235</td>
<td>47</td>
<td>6.050</td>
<td>0.15</td>
<td>6.000-6.150</td>
</tr>
<tr>
<td>23</td>
<td>2.260</td>
<td>0.05</td>
<td>2.235-2.285</td>
<td>48</td>
<td>6.150</td>
<td>0.15</td>
<td>6.100-6.250</td>
</tr>
<tr>
<td>24</td>
<td>2.325</td>
<td>0.065</td>
<td>2.297-2.362</td>
<td>49</td>
<td>6.250</td>
<td>0.15</td>
<td>6.200-6.350</td>
</tr>
<tr>
<td>25</td>
<td>2.3945</td>
<td>0.065</td>
<td>2.362-2.427</td>
<td>50</td>
<td>6.350</td>
<td>0.15</td>
<td>6.300-6.450</td>
</tr>
</tbody>
</table>


The MASTER data was flown on board the DC-8 simultaneously with the TOPSAR data during the NASA PACRIM 2000 mission. The pixel size range for DC-8 acquisition is 10-30m. In this instance a pixel size of 19.8m was captured. The data was processed and supplied by JPL as the Level –1B HDF (Hierarchical Data Format) product. The Level-IB product is subjected to radiometric calibration and provides for geo-located data. The major inputs into Level-1B processing are: raw data; calibration (spectral and radiometric); navigation data; and flight descriptors (Hook et al., 2001). Radiometric calibration for the visible-short wave infrared (VIS-SWIR) is based upon measurements from a Laboratory Integrating Sphere. Calibration of the middle infrared-thermal infrared (MIR-TIR) is based on two blackbodies (one heated and one ambient). In relation to navigation inputs, latitude and longitude for each
pixel is recorded. Aircraft attributes such as position, heading, pitch and altitude are stored as unique Scientific Data Sets (SDS) in the HDF file.

4.2.1.3. ADAR Digital Data

The ADAR system 1000 uses a Kodak Professional DCS 460 camera as a digital sensor. The camera’s CCD array is a KAF-6300 chip consisting of 2048 x 3072 pixels, each 9 x 9 mm (Dean et al., 2000). The array pixels are coated with filters to contain ¼ of red, ¼ of blue/NIR, and ½ of green pixels. Details of the calibration and application of this sensor to environmental monitoring problems are provided in Stow et al. (1996) and Phinn et al. (2000). The camera was flown twice over the sample sites used in this study to produce images with a pixel ground resolution element (GRE) of 50 cm and 1m at a height of 1.1 km and 2.2 km above ground level respectively. The focal length was 20mm with a field stop of 2.8 and an exposure time of 1/640th seconds.

4.2.1.4. Landsat ETM+ Data

A Landsat 7 ETM + image of the Mary Floodplain System captured on the 22nd August 2000 was acquired from ACRES (Australian Centre for Remote Sensing). The scene metadata and sensor characteristics are reported in Table 4.2. There is no evidence of active wildfires in the image and no smoke obscures the scene. There was also no cloud cover present.
### Table 4.2: Landsat 7 ETM + sensor characteristics and scene metadata

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>22/08/2000</td>
</tr>
<tr>
<td>Path/Row</td>
<td>105/69</td>
</tr>
<tr>
<td>Centre Latitude</td>
<td>13°01'43&quot; S</td>
</tr>
<tr>
<td>Centre Longitude</td>
<td>131°54'06&quot; E</td>
</tr>
<tr>
<td>Swath Width</td>
<td>185 km</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>30 m (Bands 1-5 &amp; 7)</td>
</tr>
<tr>
<td></td>
<td>60 m (Band 6)</td>
</tr>
<tr>
<td></td>
<td>15 m (Band 8)</td>
</tr>
<tr>
<td>Orbit Number</td>
<td>7200</td>
</tr>
<tr>
<td>Sun Elevation</td>
<td>49.9°</td>
</tr>
<tr>
<td>Sun Azimuth</td>
<td>53.2°</td>
</tr>
<tr>
<td>Average Cloud Cover (0-100)</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4.2.1.5. Ancillary Data

The primary ancillary data used is the Mary Floodplain System Vegetation map (Lynch, 1996). The data was supplied as a digital ESRI coverage containing 47 vegetation units. These units were delineated from colour infrared (CIR) aerial photos and Landsat imagery at 1:50 000 scale. The Landsat TM image was captured on the 24th June 1993 and the CIR aerial photography (Runs 1-7) was acquired on the 6th October 1993 at 1:50 000 scale.

The vegetation units were compiled from previous surveys such as land unit reports, floodplain elevation and geomorphology (Woodroffe and Mulrennan, 1993), unpublished *Melaleuca* Survey Data 1993, and other wetland surveys (Wilson *et al.*, 1991).

### 4.2.2. Trans Fly Data

The spatial extents of the data acquired for the Trans Fly site is shown in Figure 4.2. The spatial data used for this site was JERS-1 SAR and Landsat TM imagery.
Figure 4.2: Extents of spatial data used for the Trans Fly displayed over Landsat 7 ETM+ composite (RGB:5,4,3)
4.1.1.1. JERS-1 Data

JERS-1 data is single band radar imagery that was collected by the National Space Development Agency of Japan’s (NASDA) (now known as Japan Aerospace Exploration Agency [JAXA]) JERS (Japanese Earth Resources Satellite) sensor from 1992-1998. Table 4.3 lists the JERS-1 sensor parameters. JERS-1 is single band polarised data (HH) at L-band frequency (23.5 cm, 1.275 Ghz). A total of 16 scenes covering the New Guinea study area from 1995-1997 were supplied by NASDA through the Global Wetland Project as the level 2.1 processed product. The sensor parameters frequently cited (Raney, 1998) state that JERS-1 is 3 look data. However, the header files supplied with the New Guinea scenes state that the data is 4 look. The software package used to process the raw JERS-1 data was ENVI 3.5.

Six suitable scenes were selected from the original 16 scenes. The characteristics of these scenes are summarised in Table 4.4. These scenes were selected because they were captured on near anniversary dates (October-December) during 1995, 1996 and 1997. This time of the year represents the end of the dry season, with December marking the beginning of the wet season. Therefore, the landscape should be dry and relatively comparable in terms of seasonality. The effects of topography in the images are minimal as the study area is located on a flat landscape.

<table>
<thead>
<tr>
<th>Band [wavelength (cm)]</th>
<th>L (23.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>1.275</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH</td>
</tr>
<tr>
<td>Incident angle (degrees)</td>
<td>39</td>
</tr>
<tr>
<td>Orbital Direction</td>
<td>Descending</td>
</tr>
<tr>
<td>Swath Width (km)</td>
<td>75</td>
</tr>
<tr>
<td>Range resolution (m)</td>
<td>18</td>
</tr>
<tr>
<td>Azimuth resolution (m)</td>
<td>18</td>
</tr>
<tr>
<td>Looks</td>
<td>3</td>
</tr>
<tr>
<td>Pixel size (m)</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 4.3: JERS-1 sensor parameters table
<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Scene Centre</th>
<th>Path/Row</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E 140.899</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>02/10/1996</td>
<td>S 8.679</td>
<td>44/315</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E 141.012</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>03/12/1997</td>
<td>S 8.679</td>
<td>44/315</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E 141.017</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: JERS-1 scene metadata table

### 4.1.1.2. Landsat TM Data

Four Landsat TM images covering WNP and TWMA were acquired from ACRES. It is very difficult to obtain relatively cloud and smoke-free optical imagery of the region. In fact, since the advent of the Landsat series, there are only four such images. Table 4.5 summarises the scene metadata for each of these images. The quarter scene captured on the 31\textsuperscript{st} May 1997 is both cloud and smoke free. The other three scenes have cloud, active wildfires and haze present.

### 4.1.1.3. Ancillary Data

Topographic maps for the region were acquired to aid in geo-rectification and site familiarisation. Tactical Pilotage Charts at a scale of 1:500 000 of the PNG side of the international border were acquired. Acquisition of recent topographic maps of the Indonesian region was difficult due to existing sensitivities and information sharing issues. Seven topographic maps at a scale of 1:100 000 were acquired for WNP. These maps were produced by the Dutch in 1957 and were derived from aerial photography captured in the mid-1940s.

An extensive land resource survey of the Morehead-Kiunga area of PNG was conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 1971 (Paijmans, 1971a). This publication also includes
three maps at 1:500 000 scale (vegetation, geomorphology and land systems). The publication was used to gain an understanding of vegetation communities present in the region. An early vegetation survey for the Merauke area in West Papua provided a detailed description of vegetation types for the region not covered by the CSIRO survey (van Royen, 1963).

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Path/Row</th>
<th>Centre Latitude</th>
<th>Centre Longitude</th>
<th>Scene Size Ordered</th>
<th>Bands</th>
<th>Orbit Number</th>
<th>Sun Elevation</th>
<th>Sun Azimuth</th>
<th>Average Cloud Cover (0-100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20th November 1990</td>
<td>Landsat-5 TM</td>
<td>100/66</td>
<td>08°42'12&quot; S</td>
<td>140°29'45&quot; E</td>
<td>185 km x 185 km</td>
<td>1, 2, 3, 4, 5, 6, 7</td>
<td>35741</td>
<td>54.6°</td>
<td>111.7°</td>
<td></td>
</tr>
<tr>
<td>31st May 1997</td>
<td>Landsat-5 TM</td>
<td>100/66</td>
<td>08°42'09&quot; S</td>
<td>140°36'36&quot; E</td>
<td>91 km x 186 km</td>
<td>2, 3, 4, 5</td>
<td>70458</td>
<td>43.8°</td>
<td>48.0°</td>
<td></td>
</tr>
<tr>
<td>12th August 1997</td>
<td>Landsat-5 TM</td>
<td>99/66</td>
<td>08°42'57&quot; S</td>
<td>142°08'48&quot; E</td>
<td>91 km x 91 km</td>
<td>2, 3, 4, 5</td>
<td>71521</td>
<td>46.7°</td>
<td>57.0°</td>
<td></td>
</tr>
<tr>
<td>25th October 2001</td>
<td>Landsat-7 ETM+</td>
<td>100/66</td>
<td>08°42'08&quot; S</td>
<td>140°32'32&quot; E</td>
<td>185 km x 185 km</td>
<td>1, 2, 3, 4, 5, 6, 7, 8</td>
<td>13447</td>
<td>63.1°</td>
<td>99.5°</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: Landsat TM scene metadata table
4.2. PRE-PROCESSING OF DATA

4.2.1. Mary Floodplain System Data

4.3.1.1. TOPSAR Data

The TOPSAR data were processed by JPL’s Radar Data Centre and supplied in 18 look compressed Stokes Matrix format (see van Zyl and Ulaby, 1990). The backscatter intensity at HH, VV, and HV polarisations recorded by TOPSAR were extracted from the compressed stokes matrix for the L and P band together with the backscatter intensity at VV polarisation for the C-Band. The data were subjected to a 3x3 low pass filter to further suppress speckle and then converted from slant to ground range (Menges et al. 2001a,b).

Backscatter characteristics of ground targets vary depending on the incidence angle at which these are illuminated (Menges et al., 1998; Wang et al., 1997; Champion, 1996; Lin et al., 1994; Bertuzzi, 1992; and Engman, 1991). A correction for this effect of varying incidence angle has, therefore, been applied according to the methodology described in Menges et al. (1999). A histogram equalisation between every data line of constant incidence angle and one such line chosen as the ‘norm line’ is carried out using the slope of a linear regression for the magnitude components and the slope and intercept values for the complex co-polarised return. The TOPSAR data were registered to a topographic map with an RMS error of 10m and mosaiced.

4.3.1.2. MASTER Data

The MASTER data were referenced to the TOPSAR data and resampled to a resolution of 20m. Due to inherent distortions in the MASTER data, a third order polynomial function was required in this process. Using 62 ground control points (GCPs) an RMS error of less than 1 pixel (20m) was achieved. The MASTER data contains a total of 50 channels in four continuous blocks located...
in the VIS/NIR, lower MIR, upper MIR and TIR regions. Three channels in the lower MIR region (#16-18), eight in the upper MIR region (#26-28; #33-35; #36-38), and two channels in the TIR region (#41; #50) had to be discarded as these exhibited a very low signal to noise ratio. A total of 37 channels remained.

4.3.1.3 ADAR Digital Data

The ADAR data was processed in accordance with the “Program Guidelines” developed by Phinn et al. (2000). These guidelines outline the procedures used to correct for radiometric and geometric distortions (Phinn et al., 2000; Phinn et al., 2001).

Radiometric distortions occur throughout the data capture and processing cycle (the ADAR system itself, image acquisition and processing). The raw ADAR data was corrected for illumination using a vignette mask derived from calibration experiments using images derived from a Spectralon Panel (a uniformly illuminated and reflecting panel). The masks were applied to each band to reduce variation due to vignette effects in the order of 5 DN (Phinn et al., 2001). Linearity of sensor response was stable as shown by Phinn et al. (2000). Between scene radiometric variations due to the bi-directional reflectance distribution function (BRDF) were corrected for using a model incorporating a back-scattering model applied to vegetated areas in images and a forward-scattering model applied to water surfaces (Phinn et al., 2001). A linear interpolation routine was used to expand the measured array values for each scene into a complete three band image that resulted in maximised contrast in further enhancement procedures and maintained geometric integrity (Phinn et al., 2000).

First round geometric processing that placed individual frames was accurate to 200 m and enabled frame-to-frame feature matching (Phinn et al., 2001). The individual frames were then mosaiced and registered using ERDAS Orthobase making use of the GPS co-ordinates captured with each frame of data.
Control points in the data revealed that the spatial accuracy is limited to an error of 50 m.

### 4.3.1.4 Landsat ETM+ Data

The Landsat ETM scene captured in August 22\textsuperscript{nd} 2000 was registered to a 1:50 000 scale topographic map using 40 GCPs and resulted in an RMS error of less than 30m (1 pixel). The image was then resampled to 30 m resolution.

### 4.3.2 Trans Fly Bioregion Data

#### 4.3.2.1 JERS-1 SAR Data

Figure 4.3 describes the flow of processing the JERS-1 data. The images were first rotated and then a low pass 3x3 filter was applied to reduce speckle. The 1996 images were then geo-referenced to the previously registered Landsat TM images using a first order polynomial function. Image pixels were resampled using the nearest neighbour algorithm to 30 m. The 1995 and 1997 images were co-registered to the 1996 JERS-1 data and also resampled to 30 m. It is noted that the statistical properties of image data may be influenced by the registration process (Yanasse \textit{et al.}, 1997). The digital numbers of the image data represent amplitude. For the purpose of this study it was necessary to convert the data to both intensity and decibel (dB) values. As outlined in the JERS User’s Guide (NASDA, 1998) it is usually necessary to apply a radiometric conversion using the Normalised Radar Cross Section (NRCS) equation calculated by

\[ NRCS = 20 \log_{10} (I) + CF \ [dB] \]

where \( I \) is the value of each pixel ranging from 0 to \( 2^{15} \)-1. The NRCS conversion was applied to the eight image scenes.
4.3.2.2. Landsat TM Data

The two Landsat TM scenes captured on 31\textsuperscript{st} May and 12\textsuperscript{th} August 1997 were initially registered using the Dutch 1:100 000 scale topographic maps for the Wasur region, and the 1:500 000 scale Tactical Pilotage charts for the Tonda area. The RMS error using these base data sets was too great (up to 450 m in some areas of the images) and not uniform, so field GCPs were utilised. For the May 1997 image, 20 GCPs collected using a hand held GPS in the field that could be confidently located on the image were used in the registration. These points were also selected as they represented a geographic spread across the image, thereby reducing geometric distortion effects in any one part of the image.
through the resampling process. The resultant RMS error was 60 m (2 pixels). The image was resampled to 30 m resolution. Eighteen GCPs also collected in the field were used to register the August 1997 image in the same manner as the May 1997 image. The RMS error was 90 m (3 pixels) and the image was resampled to 30 m resolution.

4.4. CRITIQUE OF DATA

The radiometric and geometric integrity of datasets acquired for the Mary Floodplain System was of a high quality. The MASTER data was not radiometrically corrected to a flat field, as the application it was being used for in this project, did not require this level of calibration. It is noted, however, that spectral curves for various ground targets in the MASTER data would vary significantly if the full radiometric calibration process was applied. Between image radiometric calibration for the ADAR images was problematic because BRDF effects were still present after the processing protocols were implemented. This can be attributed to the fact that the BRDF model produced for the processing protocols was not entirely applicable to this dataset. Once again, this was not a major issue, given the application the ADAR data was being used for in this project. A small subset of a single frame was used for examining spatial resolution controls in applying the spatial statistic. Of more concern with respect to the ADAR data, is the spatial error estimate of 50 m.

One of the single largest impacts on achieving the aims of this project with the Trans Fly data sets are geo-registration inaccuracies. In using these data for quantifying biomass, it is crucial that registration error should be in the order of 10 m. In this instance, the Landsat data were subject to a RMS error of 60 m and 90 m. The JERS-1 data were registered to the Landsat TM images resulting in a RMS error of 30 m. Therefore, there is error propagation in the JERS-1 geo-registration process. Reasons for the difficulties in the geo-registration process include:

- a mismatch in base topographic mapping scale and satellite imagery;
the currency of the Dutch topographic maps;

the environment is highly dynamic, and field GCPs were collected 3-4 years after Landsat TM image capture. Therefore target features may have changed over this time frame;

there is an error associated with hand-held GPS readings that was difficult to quantify due to a lack of pre-existing control points; and

with respect to the image-to-image geo-registration process between the JERS-1 and Landsat TM data sets, some of the JERS-1 data were captured up to two years previous to the Landsat TM and at different times of the year. Therefore, finding a precise location in both images is difficult as the landscape may appear different in two scenes.
CHAPTER 5

5. METHODOLOGY

This chapter presents the methodology adopted in this study. Section 5.1 summarises the methods used for linking ground and remotely sensed data. Section 5.2 details the methods used in quantifying *Melaleuca* biomass using SAR data. An overview of the methodology adopted is given in Figure 5.1.

5.1. LINKING GROUND AND REMOTELY SENSED DATA

To evaluate the utility of the spatial statistic for determining optimal field sample plot size, it was applied to imagery derived from four imaging sensor systems: TOPSAR, MASTER, Landsat ETM, and ADAR (an overview of the characteristics of the airborne systems and satellite data along with pre-processing applied to the data prior to implementing the statistic is presented in Chapter 4.). A conceptual outline of the spatial statistic is given in Section 5.1.1. The subsets selected for this investigation are described in Section 5.1.2. Section 5.1.3 summarises the application of the spatial statistic to the data.

5.1.1 Conceptual overview of the spatial statistic

To correlate the information contained in remotely sensed data with biophysical variables for calibration or validation purposes, a ground sampling strategy should operate at a scale where the error relating image to field data due to non-measurable variance (such as mis-registration) is minimised. Neither the traditional root mean square error nor the spatial statistics currently employed in remote sensing applications address the problem of spatial registration errors in linking image data with a quantifiable biophysical attribute on the ground. A local spatial statistic was developed as a solution to accurately link image and field data. The statistic is based on the average Digital Number (DN) values within a
Assess the effect of spectral and frequency orientation controls on determining the location of suitable field plot sizes.

3. Apply spatial statistic to optical data (MASTER) across various wavelengths ranging from the blue to TIR parts of the spectrum.
4. Apply spatial statistic to multi-polarised SAR data (TOPSAR) for the L- and P-band frequencies.

Assess the effect of spatial resolution controls and the impact of locational uncertainty on determining the location of suitable field plot sizes.

3. Apply spatial statistic to NIR Band (TM Band 4) of Landsat ETM+ data (30 m resolution)
1. Apply spatial statistic to NIR Band (Band 9) of MASTER data (20 m resolution)
2. Apply spatial statistic to NIR Band of ADAR data (1m and 0.5 m resolution)

Determine the above ground woody biomass of Melaleuca on tropical floodplains from SAR data

Mary Floodplain System

6. Regression of basal area data obtained from transects (Bach, 2002) against the intensity values of the TOPSAR data
7. Apply spatial statistic to TOPSAR data and select location and size of field plots.
8. Sample field plots.
9. Regression of field biomass against the intensity value of TOPSAR data using an allometric equation (Finlayson et al., 1993)
10. Non-linear regression (hyperbolic) analysis of TOPSAR data to investigate saturation effects
11. Biomass mapped for Melaleuca

Trans Fly Bioregion

12. Field data collected
13. Regression of field biomass against the intensity value of JERS-1 data using an allometric equation (Finlayson et al., 1993)
14. Biomass mapped for Melaleuca

Figure 5.1: Flowchart outlining the methodology adopted in this study.
The statistic is calculated by shifting an image window through neighbouring locations and determining the standard deviation of the respective mean values. The procedure outlining the application of the statistic to a single point in the image is shown as a flow diagram in Figure 5.2. The positional error and the maximum lag (or window size) to consider must be pre-determined. The positional error estimate should be derived from control points that were not used in the geo-referencing procedure. The pre-determined lag (M) should result in a window size that is just beyond the logistical feasibility for fieldwork. A normalisation of the statistic is implemented to enhance the information detail on local spatial structure against the global average. The optimal lag (m) is used to produce the optimal plot size. By extracting the window size \((2m + 1)\) at which the local statistic is lower than the global average, an image can be generated, that suggests adequate plot size requirements for each image element. Appendix 2 summarises the results of the application of the statistic to test data compared with the results of the semi-variogram, which proves the validity of the statistic.
Figure 5.2: Diagrammatic representation of the procedure to calculate the spatial statistic for an image data point.

5.1.2 Subset selection

This study focuses on two habitats representative of the lower Mary Floodplain System, one being a freshwater environment dominated by a paleochannel and the other a saline environment characterised by mangroves. The
species composition and morphology of these subsets are typical of the varied habitats found in coastal wetlands throughout northern Australia. These subsets were selected because sampling of these habitats in the field to link with remotely sensed data has proved problematic in the past. The heterogeneity of the paleochannel habitat has made assessment of regenerating *Melaleuca* from remotely sensed data difficult. The mangrove habitat was chosen to test the assumption that this habitat is largely homogenous in the NIR wavelength. Both these habitats are important in examining floodplain management in terms of assessing the success of preventative saline intrusion and rehabilitation works.

The freshwater paleochannel feature (Figure 5.3A) is typified by varying water depths resulting in a varied distribution in plant communities. Deep water species such as *Eleocharis sphacelata* and *Ipomea aquatica* form discrete patches within aquatic grasslands of *Hymenachne acutigluma* and *Leersia hexandra* (Lynch, 1996). *Melaleuca cajuputi, M. viridiflora* woodland with a grassland/sedgeland understorey composed of *Oryza rufipogon* and *Eleocharis* sp. co-dominates as shown by Figure 5.4. Adjacent to the paleochannel is an area of *Melaleuca* regeneration that had previously been subject to saltwater intrusion. The mangrove habitat (Figure 5.3B) is dominated by *Sonneratia alba, Avicennia marina, Rhizophora stylosa* and *Ceriops tagal*. The surrounding flats are composed of herbs, grasses and sedges such as *Pseudoraphis spinescens, Cyperus scariosus, Merremia gemmella* and *Melochia corcorifolia* (Lynch, 1996).
Figure 5.3: Study area displaying subset (A) the freshwater paleochannel habitat, and subset (B) the saline mangrove habitat. Both subsets are displayed as MASTER false colour composites (Bands 9, 5, 3 as R, G, B respectively). The Mary Floodplain System and surrounds is highlighted by the TOPSAR strip displayed as greyscale.
5.1.3 Application of the spatial statistic

The spatial statistic was applied to the 37 channels of the MASTER data and the TOPSAR L- and P-Band polarimetric data to examine the effect of wavelength and polarisation on field sample size. Output at this scale consisted of an error estimate of one pixel for locational accuracy and a maximum field sample plot size of a 31 pixel window. The large plot sizes generated from this window size are not really feasible for field sampling and were employed to illustrate the utility of the statistic in heterogeneous environments. In investigating spatial resolution controls, the statistic was also applied to the NIR band (TM Band 4) from Landsat ETM+ data, a NIR band (Band 9) from MASTER data, and the NIR band of ADAR airborne multispectral data. The ADAR data was subjected to a maximum window size of 501 and 301 pixels (for the 50 cm and 1 m data respectively) resulting in actual plot sizes comparable to those evaluated in the coarser resolution data. However, the actual error estimate of 50 m could not be used because of the high
computational demand in relation to the maximum window size and was, therefore, reduced to an error estimate of 10 m, in this instance. This produced images whereby the plot sizes are comparable to the coarser resolution datasets, however the error estimate is unrealistic. In order to address the actual error estimate for the ADAR data, of 100 and 50 pixels (for the 50 cm and 1 m data respectively), the maximum window size was set at a 31 pixel window. This application produced images with an accurate error estimate and plot sizes that are not comparable with the coarser resolution datasets.

5.2. ESTIMATING MELALEUCA BIOMASS USING SAR DATA

The data used in estimating biomass of *Melaleuca* were the TOPSAR data (L- and P- Band) for the Mary Floodplain System and JERS-1 SAR for the Trans-Fly site. Pre-processing of these data is described in Chapter 4. The field sampling methodologies for the two sites were different and are described in this section.

Two sets of field data were used for the Mary Floodplain System in developing a relationship between *Melaleuca* and radar backscatter. The first method of field data collection is outlined by Bach (2002). The field sampling design and data collection were carried out by staff from the Department of Infrastructure, Planning and Environment (DIPE), Darwin. Coinciding with the acquisition of Landsat 7 ETM imagery (August 1999), 11 transects were sampled. These previously established sites represent the major floodplain habitats and areas that have been subject to change (e.g. invasion by weeds or saltwater). Records of monitoring sites included general habitat description, vegetation parameters (plant cover, species composition and abundance), disturbance attributes, environmental measures (water level, soil parameters), records of woody vegetation (canopy density, basal area, tree height and DBH). Sampling along transects, ranging from hundreds of metres to over 6 km in length, allowed for the large-scale assessment of wetland health. Records were made in regular intervals and at any significant change in vegetation cover. The measurements at all transect points included a subset of the
site measures above, over a 5 m x 5 m area. The basal area data (m$^2$/ha) for Melaleuca sites were regressed (simple linear regression) against the intensity values for that location from the TOPSAR data.

The second method of field sampling relied on the implementation of the spatial statistic described and the use of an allometric equation for Melaleuca biomass. Recapping, the application of the spatial statistic to image data determines the appropriate location and size of field plots (see Menges et al., 2002). The statistic was applied to the TOPSAR L- and P-Band polarimetric data providing an error estimate of one pixel for locational accuracy and evaluating the statistic to a maximum plot size of a 31 pixel window. From the resultant image, the location and size of field plots were selected before going into the field.

Melaleuca spp. swamps are not well represented in current biomass data for the tropics (Eamus et al., 2000). There has only been one study site (see Finlayson and Cowie, 1993) that has been used to develop the allometric equation for estimating the above ground woody biomass of Melaleuca forests in northern Australia. Biomass of Melaleuca can be calculated in the field by measuring the DBH of the trees (approximately 1.3 m). The relationship between DBH and biomass of Melaleuca is described by the following allometric equation (Finlayson and Cowie, 1993):

$$\text{Log (FW)} = 2.266 \times \ln (\text{dbh}) - 0.502$$

This is a single combined regression for both M. cajaputi and M. viridiflora, where biomass is calculated from fresh weight (FW). Although this equation has been obtained from one site, it is unlikely that this will contribute significantly to error in biomass estimations and relating field and image data. The regression analysis of data undertaken by Finlayson and Cowie (1993) and also reported by Eamus et al.
(2000) states that the $R^2$ value for the combined species DBH equation is 0.984 ($M.\text{viridiflora} \ R^2 = 0.987$ and $M.\text{cajuputi} \ R^2 = 0.965$). With the occurrence of hybridized specimens between these species in the field the use of the combined equation overcomes any minor discrepancies. In addition it is a fresh weight equation enabling tighter coupling with the SAR data which requires moisture to be present in the target (in this case the tree) in order to obtain a relevant signal. A comprehensive review of allometric equations and their reliability in northern Australia is provided by Eamus et al. (2000).

Field data collection in the Mary Floodplain System was conducted in accordance with the results from the spatial statistic during the 2002 wet season (March). Although field sampling occurred one and a half years after the TOPSAR data capture, the biomass of *Melaleuca* sites within this study area is not as dynamic as that in the Trans Fly Bioregion. A total of 22 field plots composed predominantly of *M. cajaputi* and *M. viridiflora* were accessed during the wet season when the study area was at maximum inundation using an airboat. Field plots were located using a hand-held GPS and were therefore accurate to within 5 m to 10 m. A corner point of the plot was located using the GPS and the remaining corners were marked out with a GPS and transect tape. The trees within the plot that had been measured for DBH were marked with bright paint to avoid double recording. The correct height for DBH measurements in flooded sites was determined by using a staff marked at 1.3 m which was placed in the water.

Field sampling in the Trans-Fly site was conducted in an *ad hoc* approach, primarily because the spatial statistic had not been developed at the time of fieldwork (WNP was sampled in May and November 2000 and TWMA was sampled in August and November 2001). Additionally, the ground conditions were not known. Plots were selected whilst travelling in the field, and DBH measurements were recorded for each tree in a plot. Plot sizes varied in relation to time and available resources. Plots that were selected were homogenous and located in the majority of instances away from borders between cover types, and assumed
(from local knowledge) to have been composed of *Melaleuca* for at least two decades. Data recorded for each plot included DBH, average height and inundation level (as evidenced by a watermark on the tree trunk). The JERS-1 images were captured in November 1995, October 1996 and December 1997. There is a four to six year difference between the time of image capture and field sampling.

The biomass data for each site was analysed by simple linear regression against the backscatter intensity from the radar data at the corresponding location. There is a linear relationship between above ground woody biomass and SAR backscatter intensity: as above ground woody biomass increases, SAR backscatter intensity also increases. Intensity values were extracted simultaneously for each channel from the TOPSAR data using an IDL program. Regression statistics were used to determine the most appropriate model for biomass estimation for both the Mary Floodplain System and the Trans-Fly site. The *Melaleuca* areas in the image data of these sites were then density sliced to appropriate biomass levels using the most suitable regression equations to produce biomass maps. Non-linear regression (hyperbolic) analysis was additionally conducted on the TOPSAR data to examine saturation effects. The Mathematica (V4.1) program to conduct this regression analysis is included in Appendix 3.

5.3. SUMMARY

- The methodology presented in this chapter addresses the fundamentally important issue of the link between remote sensing and ecological measurements in the field. The spatial statistic for determining the size and location of field plots outlined in this methodology represents an extension of the local variance suggested by Woodcock and Strahler (1987), whereby the window is expanded based on the magnitude of the anticipated registration error. A unique feature of
the spatial statistic is that it identifies candidate sites for locating field plots rather than just the size of plots.

- The effect of spectral controls on determining the location of suitable field plot sizes for linking remotely sensed data with a quantifiable biophysical parameter on the ground is investigated by applying the spatial statistic to MASTER and TOPSAR data.

- The effect of frequency orientation controls on determining the location of suitable field plot sizes for linking remotely sensed data with a quantifiable biophysical parameter on the ground is evaluated by applying the spatial statistic to the L- and P-bands of TOPSAR data.

- Determining above ground woody biomass of *Melaleuca* from SAR data is examined for the Mary floodplain system by:
  a) Applying a simple linear regression analysis to the TOPSAR data and basal area data collected from transects (Bach, 2002); and
  b) Selecting and sampling field plots after applying the spatial statistic to the TOPSAR data. The biomass of *Melaleuca* sites was calculated using an allometric equation for fresh weight (Finlayson and Cowie, 1993). Simple linear regression analysis was then conducted for biomass values and intensity value from the TOPSAR data. Possible saturation effects were evaluated by using a non linear regression (hyperbolic) analysis on the same data.

- Determining above ground woody biomass of *Melaleuca* from SAR data was assessed for the Trans Fly Bioregion by applying a simple linear regression analysis to the JERS-1 data and field data.
6. RESULTS

6.1. LINKING GROUND AND REMOTELY SENSED DATA

The following sections summarise the results for the spectral and frequency orientation (polarisation investigation) (Section 6.1.1) and the examination of spatial resolution controls (Section 6.1.2).

6.1.1. Spectral and frequency orientation (polarisation) controls

The result obtained from applying the spatial statistic for defining optimal plot sizes to a series of adjacent spectral bandwidths in a number of image data sets was that major variations in plot-sizes were not apparent. This result is demonstrated in Figure 6.1, where the output of the spatial statistical analysis, in terms of suggested plot size, is graphed against the available wavelengths from the MASTER data for four vegetation communities. There are, however, significant differences for distinct regions of the electromagnetic spectrum. All four samples of vegetation communities require larger plot sizes in the NIR region and in parts of the MIR region. These are only samples of individual pixels and more information can be obtained from examining Figure 6.2, which represents the output from the spatial statistical analysis, defining optimal field sample size for the MASTER and TOPSAR data at different wavelengths and polarisations.
Figure 6.1: Suggested plot sizes according to the statistic for single samples of four wetland cover types across the MASTER data range. The four cover types are: (a) *Melaleuca*; (b) sedgeland; (c) herbland; and (d) mangroves.

Figure 6.2A displays a series of images where each pixel in each image contains an estimate of the optimal plot sizes for characterising that portion of the paleochannel habitat and linking it to field data. Those areas of pixels that are coloured blue are the most suitable areas for field sampling as they are the smaller plot sizes (ranging from 60 m to 150 m). The interior of the paleochannel is dominated by small plot sizes throughout the spectral range of the MASTER data (6.2A(1) – 6.2A(5)). The differences between the optimal plot size images between each of the bands are mainly related to the spatial distribution of areas requiring an increased plot size. That is, some environmental features become more apparent in different spectral bandwidths, i.e. those dominated by photosynthetic vegetation, exposed soil and water bodies. The interior of the
paleochannel is completely inundated with a near complete coverage of aquatic grasses (*Eleocharis sphacelata* and *Ipomea aquatica*) form discrete patches within *Hymenachne acutigluma* and *Leersia hexandra*) at the surface. Patches of *Melaleuca* woodland occur in this environment. The presence of these woodlands in the channel is clearly indicated by the increased plot sizes identified in the near-infrared (NIR) and red channels (Figures 6.2A(3) and 6.2A(2) respectively). The variations in the suggested plot sizes for the middle-infrared (MIR) region (Figure 6.2A(4)) are not consistent with the woodland boundaries. The plot sizes suggested for the blue and thermal-infrared (TIR) wavelengths (Figures 6.2A(1) and 6.2A(5) respectively) exhibit limited variability for the interior of the paleochannel. It should be noted that the distinctive vertical line most evident in the longer wavelengths of the MASTER data is an artefact of the mosaicing process. The boundary of the paleochannel is most clearly represented at the longer wavelength shown by a suggestion of very large plot size values depicted in yellow, red, and white.

For the SAR data (Figures 6.2A(6) – 6.2A(12)) the boundaries of the paleochannel are only distinguishable in L-HV (Figure 6.2A(8)), where it is shown in white and the interior of the channel displays large variation in suggested plot sizes. The L-HH channel (Figure 6.2A(6)) has similar characteristics to the L-HV channel, but the western boundary is less clearly defined. The boundary of the channel is not evident in Figure 6.2A(7) representing L-VV. When compared with the L Band images, the P Band images display a less complex spatial patterning of plot sizes. The HH, VV, and HV polarisations (Figure 6.2A(9)-(11)) do not depict the structural boundaries of the paleochannel. The small patches of increased plot size correspond with patches of *Melaleuca*. The L-Phase image has been omitted from the figures, due to its similarity with the L-HV, thus providing little additional information. The P-Phase image represented by Figure 6.2A(12) is similar to L-HH in the paleochannel but shows a distinct difference in the western meander. This environment is dominated by dry grassland and medium to dense patches of *Melaleuca*. It appears variable in all the MASTER and SAR channels available, with least variability in NIR and P-VV.
Figure 6.2B illustrates the optimal plot sizes suggested by the spatial statistic for each pixel in a series of images depicting an area of mangrove habitat. In a false colour composite image mangroves appear in a relatively uniform red tone due to the predominance of the NIR response. Despite this uniform appearance, there were only a few small areas in the mangrove community in the NIR region that are highlighted by the statistic as being suitable for sampling (see Figure 6.2B(3)) indicated by the blue areas. That is, where the suggested plot sizes are sufficiently small to remain within the mangrove boundaries. The suggested plot sizes for mangroves in the visible (Figures 6.2B(1-2), MIR (Figure 6.2B(4)), and TIR (Figure 6.2B(5)) are small (approximately 60 m) shown by the dominance of the dark blue areas, indicating a homogeneous environment at these wavelengths. In the visible wavelengths, a linear feature can be discerned in the upper and lower reaches of the mangroves with slightly increased plot sizes (90 m – 150 m indicated by the pale blue areas). This feature also appears in the L-HV channel but not in the other SAR channels. With this exception, the L-Band polarisations (Figures 6.2B(6-7) and the P-HH (Figure 6.2B(9)) SAR image bands produce very similar results with small patches of increased variability in comparison to a very smooth response from the surrounding herbland. The response for the P-Phase image (Figure 6.2B(12) shows a marked difference with larger plot sizes suggested for the mangroves and the herblands. P-VV and P-HV (Figures 6.2B(10-11) display small plot sizes (30 m) for the herbland, but also display an increased variability in plot size within the mangroves.
Figure 6.2: Results of the spatial statistic illustrated by (A) the paleochannel habitat and (B) the mangrove habitat, for selected wavelength / polarisations: 1,2,3,4,5 : MASTER Band 1,5,9,29,49 respectively; 6,7,8,9,10,11,12 : L-HH, L-VV, L-HV, P-HH, P-VV, P-HV, P-Phase respectively.
6.1.2. Spatial resolution controls

Figure 6.3 displays the results of implementing the statistic on varying resolutions of image data for the *Melaleuca* woodland in and surrounding the paleochannel. The false colour composites are displayed in conjunction with the results of the statistic for the NIR channel of each sensor. The *Melaleuca* can be clearly seen on the ADAR image data, distinguished from the mangroves by the rough texture derived from the individual canopies. The results from analysis of the NIR channel of the Landsat ETM data show that some of the smaller patches of *Melaleuca* have not increased the local variability to such an extent that the statistic requires an increased plot size. The width of boundaries (shown by large plot sizes) increases significantly in the Landsat ETM data. Identifying a suitable sample location and size for relating NIR values to a *Melaleuca* parameter could be achieved using these results in conjunction with knowledge of the spatial pattern and distribution of *Melaleuca*.

For the purposes of on-going biomass estimation in *Melaleuca* spp., a plot size must be found that is centred within a *Melaleuca* woodland patch and does not extend beyond the boundaries. For the MASTER data such points can be identified for many of the *Melaleuca* patches including those marked as area A and B on Figure 6.3A. Using the Landsat ETM data, suitable sample points were identified in area B but not A. The high-spatial resolution ADAR data was shown to be unsuitable for sampling either of the two Melaleuca areas at A and B. The optimal field plot sample size derived from the 50 cm pixel ADAR (Figure 6.3e) produced an indication that the optimal plot size is beyond the applied limit. In comparison, the 1 m data (Figure 6.3f) is not completely white (i.e. unsuitable) within these targets and the suggested plot sizes are less than 20 m. The locational or registration error of 50 m estimated for the ADAR data is partly responsible for this result. When the ADAR data were processed using a reduced locational error of 10 m (Figure 6.3i and 6.3j), a significant increase in optimal sample size was observed in those areas that had previously been unable to define an optimal sampling regime. It should be noted that the prominent vertical lines particularly evident in the 1 m resolution ADAR images are the result of the mosaicing process.
Figure 6.3: False colour composites of sample data (a,b: ADAR 0.5, 1m; c: MASTER; d: TM) and results of the statistic. The results for the MASTER (g) and TM (h) data are shown for 20 and 30 m error estimates respectively. Two results are shown for the ADAR data representing the different error estimates (e, f: 50 m error estimate; i, j: 10 m error estimate).
6.2. ESTIMATING *MELALEUCA* BIOMASS FROM SAR DATA

6.2.1. Linear Regression Analysis of Backscatter Intensity with Fresh Weight Biomass and Basal Area: Mary Floodplain System

The 22 sites sampled for biomass in the Mary Floodplain System were selected using the spatial statistic (Table 6.1). The implementation of the spatial statistic resulted in sampling field plot sizes of approximately 30 m x 30 m, 50 m x 50 m and 70 m x 70 m at various locations. The differences in plot size are the result of image variance and locational error. Fresh weight biomass values calculated using the allometric equation ranged from 19.96-605.59 t/ha. The majority of the sites had biomass values in the range of 30-185 t/ha, and all but five sites were inundated. The sites situated on dry ground had an understorey composed of leaf litter, whilst the inundated sites had an understorey composed of aquatic grasses and sedges. The dominant species sampled was *M. cajuputi*. Some sites contained *M. leucandendra*. The allometric equation was applied to this species also. Above ground woody biomass of *Melaleuca* is a result of the number of “stems” combined with the DBH. For example, Site 2 has a relatively low biomass (63.02 t/ha) and is characterised by many stems (250), compared with Site 1, which has a relatively high biomass (259.5 t/ha) and contains significantly fewer stems (112). The biomass is higher for Site 1 because the average DBH is greater than that of Site 2 (21.6 cm and 9.4 cm respectively). Photographs of Sites 7, 8, 14, 18, 20, 21, 22 (representative of different biomass levels) are shown in Figure 6.4 (a-g) and illustrate variations in understorey, tree density and resultant biomass.
<table>
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<th>Site</th>
<th>Plot Size (Hectares)</th>
<th>Density (total no. of stems)</th>
<th>DBH (X cms)</th>
<th>Understorey</th>
<th>Biomass (t/ha)</th>
<th>Figure Reference (Figure 6.4)</th>
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<td>Inundated</td>
<td>246.12</td>
<td>g</td>
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</table>

Table 6.1: Summary of the characteristics of the Mary Floodplain System sites surveyed for biomass estimation (locations of the survey sites are displayed on a map in Figure A.4.1).
Figure 6.4 (a-c): Photographs of Mary Floodplain System sampling sites representative of a range of biomass values.
Figure 6.4 cont. (d-g): Photographs of Mary Floodplain System sampling sites representative of a range of biomass values.
The results of the simple linear regression analysis for the L-band and P-band data are summarised in Table 6.2. All regressions are significant at the 95% confidence interval, except for the P-HH and P-VV y-intercept. For this dataset, backscatter intensity at the L-band and P-VV channels is poorly correlated with biomass with $R^2$ values ranging between 0.249-0.374. Backscatter intensity from the P-HH channel is well correlated with biomass ($R^2=0.684$), however the p-value for the y-intercept is 0.11095. The P-HV channel displays the highest correlation over the entire range of biomass values sampled ($R^2=0.921$). Figure 6.5 displays the linear regression result for the P-HV channel and the upper and lower 95% confidence limits for the model. The regression equations for the P-HV model and limits are as follows:

Model: $y = 3E-05x + 0.0011$

Lower 95% Confidence Limit: $y = 2.717E-05x + 0.000222$

Upper 95% Confidence Limit: $y = 3.573E-05x + 0.002039$

<table>
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<tr>
<th>Frequency/ Polarisation</th>
<th>Regression Equation</th>
<th>$R^2$</th>
<th>P-value</th>
</tr>
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<td></td>
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<td>$y = 0.0002x + 0.0477$</td>
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<tr>
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<td>0.02127</td>
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<tr>
<td>P-HH</td>
<td>$y = 0.0004x + 0.0236$</td>
<td>0.684</td>
<td>0.11095</td>
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<tr>
<td>P-VV</td>
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<td>0.312</td>
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<tr>
<td>P-HV</td>
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<td><strong>0.921</strong></td>
<td>0.01725</td>
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</table>

Table 6.2: Regression analysis (Backscatter Intensity vs Fresh weight biomass) of L-band and P-band polarised data. All results are significant with p<0.05 (n=22), except for the P-HH and P-VV y-intercept. The $R^2$ value in bold represents the most significant correlation coefficient based on the p-values.
Figure 6.5: Linear regression results for the P-HV channel of the TOPSAR data (left), P-HV Backscatter Intensity vs *Melaleuca* fresh weight biomass (t/ha). P-HV biomass model and 95% confidence limits (right).

Due to the possibility of a double bounce interaction (particularly at L-HH and P-HH) and increased backscatter in inundated sites, a linear regression analysis was conducted on only the dry sites (n=5). The results are shown in Table 6.3. Biomass values for these sites ranged from 30.22 - 605.59 t/ha. Backscatter intensity at all channels is well correlated with fresh weight biomass, with $R^2$ values between 0.78 and 0.996. The L-HH, L-HV and P-HV regressions are significant at the 95% confidence level. Although well correlated with biomass as shown by the $R^2$ values, the L-VV, P-HH and P-VV p-values for the y-intercept fall outside the confidence interval, $p<0.05$ (0.09028, 0.66339 and 0.59504 respectively). Once again, the P-HV channel displays the strongest correlation for the biomass of dry sites ($R^2=0.996$), followed by the L-HH ($R^2=0.942$) and L-HV ($R^2=0.952$) channels.
Table 6.3: Regression analysis (Backscatter Intensity vs Fresh weight biomass) of L-band and P-band polarised data for dry plots. The $R^2$ values in bold represent the most significant correlation coefficients based on the p<0.05 (n=5).

Basal area was poorly correlated with backscatter intensity for the 33 sites sampled by the transect method as shown by the following channels: L-HH ($R^2=0.0056$); L-HV ($R^2=0.0251$); P-HH ($R^2=0.1432$); and P-HV ($R^2=0.1538$).

The regression equations for the P-HV model and 95% confidence limits were used to density slice the P-HV channel data, producing three images as shown in Figure 6.6. The biomass ranges for density slicing in terms of t/ha were 0-50, 50-100, 100-150, 150-200, 200-250, 250-300, >300 assuming the saturation point for P-band is approximately 300 t/ha.
Figure 6.6: Floodplain *Melaleuca* biomass maps for the Mary Floodplain System. Estimated biomass from the lower 95% confidence limit is represented by (a), the model is shown in (b) and the upper 95% confidence limit is displayed by (c).
6.2.2. Linear Regression Analysis of Backscatter Intensity with Fresh Weight Biomass: Trans Fly Site

The characteristics of the 35 sites surveyed in Wasur and Tonda are summarised in Table 6.4. Nineteen sites, which could be confidently spatially located, were used in the regression analysis of backscatter intensity with fresh weight biomass. As the Trans-Fly sites were surveyed prior to the development of the spatial statistic for determining plot sizes, plot sizes of 5 m x 5 m, 10 m x 10 m and 20 m x 20 m were used. Fresh weight biomass values calculated using the allometric equation for the 19 sites ranged from 33.89-415.96 t/ha. At the time of the field survey, all sites were dry, however, the degree of wet season inundation could be estimated by examining the watermark left by flooding on the tree trunks. Most of the sites are seasonally flooded. The understorey in the majority of the sites was composed of leaf litter, with a few sites having *Eleocharis* present. In comparison to the sites surveyed in the Mary Floodplain System, the Trans-Fly sites generally display higher biomass levels. Photographs of Sites 18, 20, 25 and 26 (representative of different biomass levels) are shown in Figure 6.7 (a-d).
<table>
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<tr>
<th>Site</th>
<th>Plot Size (ha)</th>
<th>Density (total no. of stems)</th>
<th>DBH (X cms)</th>
<th>Height (X m)</th>
<th>Biomass (t/ha)</th>
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* Sites used in the regression analysis

Table 6.4: Summary of the characteristics of the Trans-Fly sites surveyed for biomass estimation (locations of the survey sites are displayed on a map in Figure A.4.2).
The results of the simple linear regression analysis for the three years of JERS-1 data are summarised in Table 6.5. None of the y-intercepts are
significant at the 95% confidence interval, however the $R^2$ value of 0.647 for the 1995 dataset indicates a positive correlation. Due to the coefficients being close to zero, the y-intercept was set at 0 and the data was regressed again, with the results shown in Table 6.6. The 1995 and 1996 are significant at the 95% confidence interval. Figure 6.8 shows the regression result for the 1995 dataset and the upper and lower 95% confidence limits for the model. The regression equations for the model and limits produced from the 1995 dataset are as follows:

Model: $y = 0.0005x$

Lower 95% Confidence Limit: $y = 0.000442544x$

Upper 95% Confidence Limit: $y = 0.000588254x$

<table>
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<th>Year</th>
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<th>P-value</th>
</tr>
</thead>
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<td>$y = 0.0005x + 0.0085$</td>
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<td>$y = 0.0007x + 0.1224$</td>
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<td>0.10891</td>
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</table>

Table 6.5: Regression analysis (Backscatter Intensity vs Fresh weight biomass) of JERS-1 data from 3 different years (1995-1997). The $R^2$ value in bold represents the strongest correlation (n=19).

<table>
<thead>
<tr>
<th>Year</th>
<th>Regression Equation</th>
<th>$R^2$</th>
<th>P-value (Coefficient)</th>
</tr>
</thead>
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Table 6.6: Regression analysis with the y-intercept set at 0 (Backscatter Intensity vs Fresh weight biomass) of JERS-1 data from 3 different years (1995-1997). The 1995 and 1996 dataset results are significant with p<0.05 (n=19). The $R^2$ value in bold represents the strongest correlation.
Figure 6.8: Linear regression results for the JERS-1 1995 data (top), L-HH Backscatter Intensity vs *Melaleuca* fresh weight biomass (t/ha). JERS-1 1995 biomass model and 95% confidence limits (below).

The regression equations for the 1995 data model and 95% confidence limits were used to density slice the 1995 data, producing three images as shown in Figure 6.9. The ranges for density slicing in terms of t/ha were 0-50, 50-100, 100-150, >150, assuming the saturation point for L-band is 150 t/ha.
Figure 6.9: Floodplain Melaleuca biomass maps for the Trans Fly site. Estimated biomass from the lower 95% confidence limit is represented by (a), the model is shown in (b) and the upper 95% confidence limit is displayed by (c).
6.2.3. Non-Linear Regression (Hyperbolic) Analysis of Backscatter Intensity with Fresh Weight Biomass: Mary Floodplain System

The results for the non-linear regression analysis on the L- and P- Band TOPSAR data are displayed in Figure 6.10. Calculation of coefficients and regression analysis was achieved by fitting a hyperbolic function defined by the following equation:

\[-a / (x-b) + c = y\]

Where:
- \(x\) = Biomass (t/ha)
- \(y\) = Backscatter (Intensity)
- \(a\), \(b\) and \(c\) are parameters

All regressions are significant at the 95% confidence interval. The models for the L-VV and P-VV channels are over-predicting, particularly in the P-VV channel where all but three points are below the curve. The model for the P-HV channel appears to indicate that within the range of biomass sampled, there is no saturation effect.
Figure 6.10 (a-f): Non-linear regression results (Hyperbolic) for the L- and P-Band channels of the TOPSAR data.
6.3. SUMMARY

6.3.1. Spectral and frequency orientation (polarisation) controls

- There were no apparent major variations in plot sizes generated by the spatial statistic for *Melaleuca*, sedgeland, herbland and mangrove cover types when applied to adjacent spectral bandwidths in MASTER data.
- There are, however, significant differences for distinct regions of the electromagnetic spectrum. The above-mentioned cover types require larger plot sizes in the NIR region and in parts of the MIR region.
- Boundaries between cover types (e.g. the edge of the paleochannel feature) are defined by the spatial statistic as the largest plot sizes.
- The results of the spatial statistic for the TOPSAR data indicate a less complex spatial patterning of plot size for the L-band channels compared with the P-band channels (the exception is the P-Phase image).

6.3.2. Spatial resolution controls

- Data with a high spatial resolution (e.g. ADAR data) provide more areas of small plot sizes for sampling *Melaleuca* compared to lower resolution data (e.g. Landsat ETM+) provided the spatial error is minimised.

6.3.3. Estimating *Melaleuca* biomass from TOPSAR data: Mary Floodplain System

- Twenty two sites in the Mary Floodplain System were sampled for *Melaleuca* biomass in accordance with the spatial statistic and ranged from 19.96-605.59 t/ha in fresh weight biomass.
- There was a high correlation (R²=0.921) between fresh weight *Melaleuca* biomass sampled in accordance with the spatial statistic, and TOPSAR P-HV channel backscatter intensity.
• There was a high correlation between fresh weight *Melaleuca* biomass and TOPSAR backscatter intensity for all channels when examining dry sample sites only (n=5).
• There was a low correlation between the pre-existing Mary Floodplain System *Melaleuca* basal area transect data and TOPSAR backscatter intensity values.
• Non-linear regression analysis (hyperbolic) indicates that there is no saturation effect for the TOPSAR P-HV channel.

6.3.4. Estimating *Melaleuca* biomass from JERS-1 data: Trans Fly Site

• Thirty five sites were sampled for *Melaleuca* biomass without using the spatial statistic. Of these sites only 19 could be accurately located spatially. For the 19 sites the fresh weight biomass ranged from 33.89-415.96 t/ha.
• There was a significant correlation ($R^2=0.643$) between fresh weight *Melaleuca* biomass and backscatter intensity from the 1995 JERS-1 data.
CHAPTER SEVEN

7. TECHNICAL DISCUSSION OF THE RESULTS AND EVALUATION OF METHODOLOGY

7.1. LINKING GROUND AND REMOTELY SENSED DATA

The results obtained from applying the spatial statistic for estimating an optimal field plot size to sample, taking into account positional errors, indicated that the optimal plot sizes varied according to spectral band (location and width) and polarisation. It is well known that each spectral bandwidth and polarisation responds differently to existing ground parameters (Atkinson and Emery, 1999; Atkinson et al., 2000; Wang et al., 2001). The mangroves, for example, appear more homogenous at the MIR and TIR wavelengths, while consistently larger plot sizes were recommended for the NIR band. This result agrees with the study conducted by Chavez (1992). Both TIR and MIR responses from vegetated and bare surfaces were predominantly determined by the presence of moisture, which is a relatively constant parameter within this habitat. The NIR, on the other hand, is determined by the leaf cell structure and, therefore, highly sensitive to differences in leaf density, health, and species composition. The variation in these parameters is reflected in the high local variability in this habitat indicated by the results of the statistic.

Another example is the result for the SAR data in the paleochannel. At L-HH and L-HV, the local variability, as shown by the spatial statistic, is high within the channel even where the cover is solely composed of aquatic grasses. In contrast, the P-polarisation responses show minimal variability where there is no occurrence of Melaleuca, indicating that these channels are not sensitive to the variation that is being recorded at the L-Band and that exists within the aquatic grasses on the ground. This lack of sensitivity in specific bandwidths to certain ground parameters can be seen as information the statistic is able to extract from the data in an easily interpreted manner. Areas that show little variability can either be explained by the channel’s lack of sensitivity to variability that does exist in reality, or by a real lack of variability recorded by
the particular instrument for the ground target. The latter is most frequently observed in moderate resolution data of less spatially complex environments, such as agricultural fields under crop, or large scale forestry plantations. Obviously, if sampling location and plot size for relating ground parameters to a channel or set of channels have to be chosen in such an environment where there is minimal local variability, then the results of the statistic are not of great significance.

Based on the assumption that there is always variation present in a natural environment (Dungan et al., 1994), the amount of variability presented in a given data channel can be seen as an indication of the channel’s sensitivity to the target parameters. In the case of mangroves in this study, the NIR channel, which exhibits the greatest local variability, would clearly hold the most important information in regard to the target’s bio-physical parameters. Identifying suitable sample location and sites in this environment is not a trivial task, as the error associated with measurements derived from a given sample plot are likely to vary significantly for small shifts in plot location. Given the uncertainty associated with image to ground registration this error transfers directly as an error in statistically relating image to ground data. The statistic is particularly useful in these circumstances to determine a location for sample plots and a plot size, which minimises this error.

A similar problem exists in the Melaleuca woodland environment. If, for example, a quantitative relationship between the above ground biomass and SAR response is to be developed, a suitable field sampling strategy needs to be implemented. The SAR channels that are likely to be related to the ground parameter, according to the literature, show very high local variability representing this complex habitat. One possibility would be to accept that there is a significant error between field measurements and image data and implement a large sample size to reduce the error component. However, this approach is extremely intensive in terms of monetary cost and time, especially in a wetland environment, where access is difficult. An alternative method is to minimise the error by identifying all suitable sample locations with associated plot sizes using the statistic and selecting a random sample from this subset.
Spatial resolution of an image is an important factor in determining the level of detail represented in the data. With increasing resolution the high frequency variation that exists is captured as shown by the ADAR imagery, where individual trees can be identified. Previous research has attempted to identify the optimum resolution of image data for specific applications (Marceau et al., 1994a, b; Atkinson and Curran, 1997; Phinn et al., 2000; Menges et al., 2001). The assumption in this research was that such an optimal resolution is determined by the ground cover characteristics. The results of this study, however, show that the optimum sample size is dependent on the image data as well as the ground characteristics. The methods for establishing the optimum resolution attempted to identify a single value that is most appropriate for the whole study area or habitats in a given application. The identification of suitable sample sizes using the statistic acknowledges that it is a locally dependent variable and an optimum sample size is calculated for each pixel in the image data. It follows that, given the ability to identify the most appropriate sample size locally, the highest resolution imagery should provide the best results for investigating image to ground relationships at any scale. The utilisation of local averages for relating ground to image data provide the spatial aggregate necessary for a meaningful interpretation. The results of this study confirm that the highest resolution data provide the largest scope for selecting suitable plots in the varied environment of the sample area. This is especially evident for occurrences of *Melaleuca* patches of small spatial extent.

Comparison of the results of the statistic for the ADAR data using a spatial error of 10 and 50 m demonstrated that the impact of registration error on suitable sample locations is considerable. Using an error estimate of 50 m, there are no areas in the data, where *Melaleuca* could be sampled for a quantitative comparison. High resolution data is, therefore, only of advantage if the spatial registration is suitably accurate.
7.2. ESTIMATING *MELALEUCA* BIOMASS USING SAR DATA

The results of the simple linear regression analysis for the Mary Floodplain System demonstrate that the P-HV normalised backscatter coefficient is highly correlated with above ground biomass of floodplain *Melaleuca* habitats. This may be explained by effects of canopy structure and tree density on backscatter intensity. This result is in accordance with other studies (Israelsson *et al.*, 1994; Rauste *et al.*, 1994; Hoekman and Quinones, 1998). The P-HV channel results utilising the field plots suggested by the spatial statistic displayed the highest correlation over the entire range of biomass values sampled. Although not significant, the P-HH response shows some potential to quantifying above ground biomass. The understorey composition may be a determinant in this channel as there is most likely a double bounce interaction between the trunk and surface. Some of the field plots were situated on dry ground with an understorey composed of leaf litter, whilst others were inundated and composed of an aquatic grass understorey or open water in the woodland habitats. It has been shown by Hoekman and Quinone (1998), that there is increased backscatter for under canopy flooding. In the Mary Floodplain System, *Melaleuca* trunks may be absorbing water and increasing backscatter through a double bounce interaction with a flooded understorey. This scenario has been reported by Rignot *et al.* (1997). The poor correlation between the L-Band data and biomass is most likely due to the saturation effect and understorey composition. The results from the regression analysis of the L-Band channels and dry sites (in the range of 30.22-605.59 t/ha) showed strong and significant correlations at L-HH and L-HV indicating that under canopy flooding affects the response at this wavelength. This is an important factor to take into consideration when acquiring satellite SAR data for these habitats. With the future launch of quad-polarised L-Band satellites, it is suggested that image and ground data acquisition be conducted late in the dry season when there are habitats that are not inundated.

The importance of applying the spatial statistic developed for this thesis in determining location and size of field plots was highlighted in a study conducted by Collins (2004). Collins (2004) correlated TOPSAR backscatter
intensity with biomass in the Wildman River Reserve savanna woodlands adjoining the Mary Floodplain System, implementing the spatial statistic developed for this thesis to collect field data. The study demonstrated a strong correlation between L-HV backscatter and above ground biomass with $R^2 = 0.91$.

The poor results for the basal area data for the Mary Floodplain System can be attributed to the fact that the field sampling strategy was insufficient in taking into account image variance and locational error. Field sampling for studies examining SAR backscatter and above ground biomass usually use large plot sizes in the order of 100 m x 100 m (Foody et al., 1997; Harrell et al., 1997). Due to time constraints Luckman et al., (1997) used plot sizes measuring 10 m x 50 m which was suitable for young forests, however as stated by the authors, this led to under sampling of biomass density in mature forests. The implementation of the spatial statistic in determining size and location of field plots in this study was a key factor in linking the image and ground data and obtaining meaningful relationships. Good correlations between basal area and L-HV backscatter have been reported ($R^2 = 0.89$) with the implementation of the spatial statistic developed for this thesis (Collins, 2004).

The results of the Tran-Fly site also illustrate the importance of implementing the spatial statistic from the outset of the investigation. With the implementation of the statistic in selecting location and size of field plots, the results for the JERS-1 data may have been improved significantly. Unfortunately, the statistic had not been developed at the time of field sampling in the Trans Fly Bioregion. Prior information about the spatial variability in the study area is crucial in designing a suitable field sampling strategy (de Gruitjer, 1999). The remoteness and difficulties in conducting field sampling in this region precluded an ample field sampling strategy. Sources of error in correlating JERS-1 backscatter with above ground biomass include the following:

1. Seasonal variability- although near anniversary dates (October, November and December), the timing of the wet season may have been different between the years resulting in some flooding. In
addition, the effects of fire may have been more prevalent in one year compared to another.

2. There is a substantial time lag between the image acquisition (1995, 1996, and 1997) and field sampling (2000-2001). The landscape in this region is highly dynamic and some *Melaleuca* forests may have been killed by fire, whilst others may have become established since the time of image capture. This was counteracted to a certain extent by using local knowledge to sample mature habitats that had been present and relatively unchanged for a “long time”.

3. Uncertainty in linking ground and image data. Linked to this is the fact that the plot sizes were probably too small at 5m x 5m, resulting in underestimation of the biomass. Plot size is related to the size of the objects to be measured (in this study *Melaleuca* trunks). If the plot size is too small in relation to the objects being measured, then the sampling accuracy and precision will be affected (Barbour *et al.*, 1987). In calculating the size of fixed area plots in an ecological context to account for between ten and twenty trees (Australian Greenhouse Office, 2001) the following is true:

- The plot size of 5m x 5m for the Trans Fly Site 2 may have been adequate in sampling for biomass as the fixed area plot equates to less than 7m x 7m (50 m²).
- The plot size of 5m x 5m for the Trans Fly Site 11 was too small and required a plot size of 8.5 m x 8.5 m (75 m²).
- The plot size of 5m x 5m for the Trans Fly Site 19 was adequate with a total stem density of 102 and average DBH of 3.2 cm. This was an encroachment site.

4. Lack of significant backscatter controls at L-Band scale in the Trans Fly study site.

The statistically insignificant y-intercept p-values are most likely due to the saturation effect at L-Band. The use of satellite quad-polarised L-Band data would be suitable in examining the lower biomass *Melaleuca* encroachment
habitats, given the studies linking secondary forest with SAR backscatter (Luckman et al. 1997; Yanasse et al., 1997). This capability would be advantageous in monitoring landscape change in this context and developing management strategies.

Saturation effects were examined through the non-linear regression analysis for the Mary Floodplain System TOPSAR data. There were too few data points to establish a true asymptote, however, the same is true for assuming that the data is non-asymptotic. Based on the limited data points, there appears to be a saturation point in all L- and P-Band polarisation combinations (at greater than 300 t/ha). In contrast, the P-HV channel did not exhibit a saturation point. Figure 6.3 shows a levelling out of the data points between 325t/ha and 495 t/ha indicating this, however, the saturation point in this particular data set can only be assumed because of the limited data points in the saturation range for the P-band as reported in the literature. The non-linear (hyperbolic) model generated for the P-HV channel does not indicate a saturation point therefore the results are inconclusive. Under canopy flooding and specular reflection in inundated woodland sites with open water may be responsible for the hyperbolic model over-predicting in the L-VV and P-VV channel. Overall, examination of these models shows that the L-Band appears to saturate before the P-Band, which is particularly evident in the L-HH channel, where the curve is flattening out. This result is in accordance with the literature.

7.3. ISSUES WITH EMPIRICAL REGRESSIONS WHEN USING REMOTELY SENSED DATA

It is important to note that in remote sensing investigations based on establishing empirical models between remotely sensed data and a biophysical variable that very few studies to date have addressed the limitations of relying on ordinary least squares regression (OLS). Furthermore, the remote sensing literature rarely addresses regression theory and the options for its applications (Cohen et al., 2003). Cohen et al. (2003: 562) state that “a violation of
assumptions about measurement error can have undesirable effects on OLS estimates of the biophysical variable”. In their paper, the authors present an improved strategy for regression modeling of biophysical variables in remote sensing. The strategy involves applying reduced major axis (RMA) models to canonical correlation analysis (CCA) indices in order to obtain LAI from Landsat ETM+ data.

The regression technique applied in this thesis may not be the most appropriate analysis of the relationship between backscatter intensity and biomass. Cohen et al. (2003) highlight issues with applying OLS to this scenario. The main issue is that the regression method assumes there is no measurement error in vegetation reflectance and/or the biophysical variable. However, in this thesis, measurement error due to location has been addressed prior to the regression process. The results for the Trans Fly JERS-1 data could be significantly improved through the use of a multi-date regression as suggested by Cohen et al. (2003). This is a research area that the remote sensing discipline needs to develop further. The robustness of the Mary Floodplain System model can be further improved through collection of more field plots, with a proportion being used as observation samples. This will enable bias to be calculated and the comparison of various regression techniques.
CHAPTER EIGHT

8.1. SUMMARY

The major focus of this thesis was to estimate Melaleuca biomass on tropical floodplains using remotely sensed data. The study areas were the Mary Floodplain System, northern Australia, and the floodplains of the Trans Fly Bioregion, southern New Guinea. In order to achieve the major focus, two specific key issues were addressed: the linking of field data to precise locations in remotely sensed imagery; and the selection of an appropriate remote sensing technology for mapping Melaleuca above-ground woody biomass. In addressing these two issues, this thesis demonstrates that above-ground woody biomass of Melaleuca species on tropical floodplains can be determined from SAR data.

In determining the factors contributing to the accurate linking of ground data with image data for estimating a biophysical variable (biomass), a spatial statistic was applied to various remotely sensed image data sets. Neither the traditional root mean square error nor the spatial statistics currently employed in remote sensing applications address the problem of spatial registration errors in linking image data with a biophysical parameter on the ground. The statistic used in this study is a local statistic based on the average values within a window of increasing dimensions and assesses the variation occurring through a positional error element. This spatial statistic was used to: firstly, assess the effect of spectral and frequency orientation controls on determining the location and size of field plot sizes from remotely sensed data; and secondly evaluate spatial resolution controls and the impact of locational uncertainty on determining the location and size of field plots.

The results obtained from applying the spatial statistic for estimating an optimal field plot size and location to sample, taking into account positional errors, indicated that the optimal plot sizes and locations varied according to spectral bandwidth (location and width) and polarization (in the case of SAR data). It was shown that
the statistic does not simply provide a measure of homogeneity (or conversely heterogeneity), but highlights spatially where the local variance is less than the global average. Therefore, the boundaries or ecotones of highly variable features and their adjacent habitats are well defined. These ecotone regions are displayed as the largest plot sizes by the statistic.

In relation to spatial resolution controls, the results of this study show that the optimum sample size is dependent on the image data as well as the ground characteristics. The results confirm that the highest resolution data provide the largest scope for selecting suitable plots in the varied environment of the test area only if the spatial registration is comparatively accurate. This fact was highlighted by the ADAR data by using a spatial error of 10 and 50 m. It was clearly demonstrated that the impact of registration error on suitable sample locations is considerable. Using an error estimate of 50 m, there are no areas in the data, where Melaleuca could be sampled for a quantitative comparison.

The results of the implementation of the spatial statistic to various image data sets shows that it is important that results from one sensor/image are not transferred to other sensors/images. It is suggested that the spatial statistic is implemented at the outset of any remote sensing investigation that links image data with field data relating to biophysical parameters.

It was determined through an extensive literature review that quad-polarised SAR data was the most suitable remotely sensed data by which to estimate above ground woody biomass of Melaleuca habitats in tropical floodplain environments. It is clear that the P-HV channel is most suitable for this task, as the L-Band channels are susceptible to saturation effects at lower biomass levels and the co-polarised P-band channels appear to be affected by understorey responses. The results of the JERS-1 analysis show some promise for examining Melaleuca encroachment in the Trans-Fly Bioregion. However, these results are not conclusive due to the time lag between the acquisition of image and field data, and the dynamic nature of the
environment. There is the potential to use future space borne L-Band sensors with quad-polarisation for this task.

This study has also demonstrated that quantifying biomass relies on accurately locating sites and determining an appropriate plot size for field sampling. This was achieved through implementing the spatial statistic. The poor results obtained from the transect/point data highlight the importance of linking ground and image data in terms of plot size and location.

8.2. IMPLICATIONS FOR FUTURE RESEARCH

This research has formed a basis for further development of models and research related to quantifying the above ground biomass of wetland forest habitats in the tropics of the northern Australia and New Guinea. With the impending launch of JAXA’s ALOS satellite system late in 2005, there is the opportunity to obtain L-HH and L-HV data at 10 m resolution for the study regions. This will enable further SAR data capture for the Trans Fly Bioregion site, and field sites within the region to be collected using the spatial statistic. A suitable regression model can then be established using multi-date imagery. With a robust model, it is assumed rapid *Melaleuca* encroachment with the study region can be effectively quantified and monitored.

Further work can be conducted on the effect of understorey composition and flooding on SAR backscatter. The effect of flooding is evident from the correlations obtained from this study between L-band data and both wet and dry sites. The dry sites displayed a good correlation between L-HH and L-HV backscatter and biomass. This is in accordance with the literature. In future investigations, dry sites need to be incorporated more fully. The effect of understorey composition (aquatic grasses) needs to be examined in more detail also.
Regression analysis techniques and their appropriate use is another area of further research. This is a research area that the remote sensing discipline needs to develop further. The robustness of the Mary Floodplain System model can be further improved through collection of more field plots, with a proportion being used as observation samples. This will enable bias to be calculated and the comparison of various regression techniques.

Finally, the input of the above ground woody biomass model in the Mary Floodplain system could be linked with biogeochemical models relating to methane and carbon. These biogeochemical models do not exist at present but it is a relevant future research direction that would contribute to furthering the knowledge we have on the role of the remote floodplains of tropical northern Australia.
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APPENDIX ONE

IDL Code: Spatial Statistic for Determining Appropriate Field Plot Size to Link Image and Ground Data.

The following is the source code for a program written by Dr. Carl Menges in IDL (ENVI 3.5). This program calculates the optimal plot size of each pixel in an image by shifting an image window through neighbouring locations and determining the standard deviation of the respective mean values. The positional error and maximum lag is pre-determined. By extracting the window size at which the local statistic is lower than the global average, an image is generated with plot size values assigned to each pixel in the form of a colour.

**pro point_stat5**

; sd of means for a shift of 'locational error' in centre
; location relative to the average of centre window
; operates one band at a time rather than whole image in memory
; Number of random samples is suggested as 2% of total but user can change it
; result in byte format - limit is restricted to 255

;******************GET INPUT******************
error=1
infilename='<filename>'
outfilename=infilename+'_plotsize'
datfilename=infilename+'_global_error_'+strtrim(string(error),2)+'.csv'
rep=1 & global=0 & limit=15 & num=0
while rep eq 1 do begin
  base = WIDGET_BASE(/COLUMN, title="INPUT PARAMETERS FOR PLOTSIZE STATISTICS CALCULATION")
  fchild = WIDGET_BASE(base, /COLUMN)
  field1 = CW_FIELD(base, TITLE = "$...........................Note:....................", xsize=34, VALUE="*Press <ENTER> after changing values*", /string, /noedit)
  field2 = CW_FIELD(base, TITLE = "Input file: ", xsize=70, VALUE=infilename, /string, /all_EVENTS)
  field3 = CW_FIELD(base, TITLE = "Output file:", xsize=70, VALUE=outfilename, /string, /all_EVENTS)
  field4 = CW_FIELD(base, TITLE = "Maximum Lag (Window=Lag*2+1):", VALUE=limit, /integer, /return_EVENTS)
  field5 = CW_FIELD(base, TITLE = "Locational Error (in pixels):", Value=error, /integer, /return_EVENTS)
  field8 = CW_FIELD(base, TITLE = "", xsize=64, VALUE="*NUMBER OF RANDOM SAMPLES FOR GLOBAL STATS CALCULATION*", /string, /noedit)
  field6 = CW_FIELD(base, TITLE = "Number of Samples:", Value=num, /long, /return_EVENTS)
  field10 = CW_FIELD(base, TITLE = 'Percentage Equivalent:', Value=per, /float, /return_event)
  field7 = CW_FIELD(base, TITLE = "Global Stats file to be created):", xsize=70, VALUE=datfilename, /string, /noedit)

  bchild = WIDGET_BASE(base, /ROW)
  ok = WIDGET_BUTTON(bchild, VALUE='OK', UVALUE = "OK")
  cancel = WIDGET_BUTTON(bchild, VALUE='CANCEL', UVALUE = "CANCEL")

  widget_control, base, /realize
  flag = 0
  while (flag eq 0) do begin
event = WIDGET_EVENT(base)
case 1 of
  (event.id eq field2): begin
    widget_control, field4, get_value = limit
    widget_control, field5, get_value = error
    widget_control, field6, get_value = num
    infilename=DIALOG_PICKFILE(Title='Select the Input Image file')
    read_header,Infilename, samples,lines,bands,inter.type
    pixels=float(samples)*float(lines)
    num2= long((2*pixels/100))
    if num2 GE 30000 then num=30000 else num=num2
    per=(num/pixels)*100
    outfilename=infilename+'_plotsize'
    datfilename=infilename+'_global_error_'+strtrim(string(error),2)+'.csv'
    flag = 1 & rep=1
  end
  (event.id eq field3): begin
    widget_control, field2, get_value = infilename
    widget_control, field4, get_value = limit
    widget_control, field5, get_value = error
    widget_control, field6, get_value = num
    widget_control, field7, get_value = datfilename
    outfilename=DIALOG_PICKFILE(/write,file=outfilename)
    flag = 1 & rep=1
  end
  (event.id eq field4): begin
    widget_control, field2, get_value = infilename
    widget_control, field3, get_value = outfilename
    widget_control, field4, get_value = limit
    widget_control, field5, get_value = error
    widget_control, field6, get_value = num
widget_control, field7, get_value = datfilename
if limit gt 254 then begin
  print, 'Maximum Lag must be less than 255!'
  limit=254
endif
flag = 1 & rep=1
end
(event.id eq field5): begin
  widget_control, field2, get_value = infilename
  widget_control, field3, get_value = outfilename
  widget_control, field4, get_value = limit
  widget_control, field5, get_value = error
  widget_control, field6, get_value = num
  widget_control, field7, get_value = datfilename
  if error GT 255 then error = 255
  if global eq 0 then
datfilename=infilename+'_global_error_'+strtrim(string(error),2)+'.csv'
    flag = 1 & rep=1
  end
(event.id eq field6): begin
  widget_control, field6, get_value = num
  widget_control, field10, get_value = per
  per=(num/pixels)*100
  flag = 1 & rep=1
end
(event.id eq field10): begin
  widget_control, field6, get_value = num
  widget_control, field10, get_value = per
  num=pixels*per/100
  flag = 1 & rep=1
end
(event.id eq ok): begin
    widget_control, field2, get_value = infilename
    widget_control, field3, get_value = outfilename
    widget_control, field4, get_value = limit
    widget_control, field5, get_value = error
    widget_control, field6, get_value = num
    widget_control, field7, get_value = datfilename
    flag = 1 & rep=0
    end

(event.id eq cancel): stop
else: flag=0
endcase
endwhile ;flag=0

WIDGET_CONTROL, event.top, /DESTROY
infilename=infilename[0] & outfilename=outfilename[0] &
datfilename=datfilename[0]

endwhile; rep=1
openr.inf,InFilename, /get_lun

;************************ end of input section**************************

;************Case Global Stats calculation - ************
;set up array for image
case type of
    1: img=bytarr(samples,lines)
    2: img=intarr(samples,lines)
    4: img=fltarr(samples,lines)
else: stop
endcase

m=fltarr(error*2+1,error*2+1)
sd=dblarr(limit+2,bands)

for b=0,bands-1 do begin
print, 'Generating global stats for band',b+1,' with a locational error of',error
readu,inf,img ;read one band
for u=long(1),num do begin ;random iterations
;select random point
x1=round(randomu(rand)*(samples-6-(limit+error)*2))+limit+error+3
y1=round(randomu(rand)*(lines-6-(limit+error)*2))+limit+error+3
while img[x1,y1] eq 0 do begin ;ignore 0s
    x1=round(randomu(rand)*(samples-6-(limit+error)*2))+limit+error+3
    y1=round(randomu(rand)*(lines-6-(limit+error)*2))+limit+error+3
endwhile
i=0
while i LE limit+1 do begin
    dim=(i*2+1)^2
    for y=-error,error do begin
        for x=-error,error do begin
            base=img[x+x1-i:x+x1+i,y+y1-i:y+y1+i]
m[x+error,y+error]=total(base)/dim
        endfor;x
    endfor;y
    av=m[error,error]
m=(m-av)^2
    sd[i,b]=sd[i,b]+sqrt(total(m)/((error*2+1)^2))
i=i+1
endwhile
endfor ; num

endfor ;bands
sd=sd/num

openw,datf,datfilename, /get_lun
writeu,datf,'lag'
for b=0,bands-1 do writeu,datf,',',string(b+1),'sd-',strtrim(string(error),2)
writeu,datf,byte(13),byte(10)

for i=1,limit+1 do begin
  writeu,datf,string(i)
  for b=0,bands-1 do writeu,datf,',',string(sd[i,b])
  writeu,datf,byte(13),byte(10)
endfor ;i

free_lun,datf
print,'Global stats calculated using ',num,' random points and written to ',datfilename

;**********end global stats calculation**********
print,'wrong file'
stop
endif
point_lun,datf,0
all=fltarr(bands,count)
readf,datf,s
for i=0,count-1 do begin
  readf,datf,s
  parts = STR_SEP(s, ',', /trim)
  all[*,i]=float(parts[1:bands])
endfor
free_lun,datf

;Calculate the stats for every point in the image
;get sd for shifting box
openw,outf,outfilename, /get_lun
point_lun,inf,0 ;make sure file is back at beginning
m=fltarr(error*2+1,error*2+1)
sd=dblarr(limit+1,bands)
result=bytarr(samples,lines)
edge=limit+error+3
for b=0,bands-1 do begin
  readu,inf,img
  result[*,*]=0 ;reset output array
  print, 'Creating plot size image for band ',b+1
  for l=edge,lines-edge do begin
    for s=edge,samples-edge do begin
      if img[s,l] ne 0 then begin
        i=0
        while (i LE limit) and (result[s,l] eq 0) do begin
          dim=(i*2+1)^2
          ...
for y=-error,error do begin
for x=-error,error do begin
base=img[s+x-i:s+x+i,l+y-i:l+y+i]
m[x+error,y+error]=total(base)/dim
endfor;x
endfor;y
av=m[error,error]
m=(m-av)^2
sd[i,b]=sqrt(total(m)/((error^2+1)^2))
if (((sd[i,b]-all[b,i])/(sd[i,b]+all[b,i]) LT 0) then result[s,l]=byte(i)
i=i+1
endwhile
if (result[s,l] eq 0) then result[s,l]=byte(limit+1)
endif
endfor;samples
endfor;lines
writeu,outf,result
endfor;bands

write_header,outfilename,samples,lines,bands,inter,1,"
free_lun,inf,outf
print,'Processing completed
end

pro read_header,filename,samples,lines,bands,inter,type
;read headerfile
parts = STR_SEP(filename, '.', /trim)
header_name = parts[0] + '.hdr'

get_lun, hdr
openr, hdr, header_name

header="
s="
;Get samples
while s NE 'samp' do begin ;skip to samples
  readf,hdr,header
  s=strmid(header,0,4)
endwhile
parts = STR_SEP(header, '=')
samples=long(parts[1])

;Get Lines
readf,hdr,header
parts = STR_SEP(header, '=')
lines=long(parts[1])

;Get Bands
readf,hdr,header
parts = STR_SEP(header, '=')
bands=long(parts[1])

;Get Header Offset
readf,hdr,header
parts = STR_SEP(header, '=')
offset=long(parts[1])

;Get Data Type
while s NE 'data' do begin ;skip to data type
  readf,hdr,header
  s=strmid(header,0,4)
endwhile
parts = STR_SEP(header, '=')
type=long(parts[1])

; Get interleave
while s NE 'inter' do begin ; skip to interleave
  readf,hdr,header
  s=strmid(header,0,5)
endwhile
parts = STR_SEP(header, '=')
inter = parts[1]

free_lun,hdr
end

pro write_header,file,samples,lines,bands,inter,type,bandnames

; Get header filename
file = strtrim(file,2)
pos = strpos(file,'.',0)
if pos GE 0 then name = strmid(file,0,pos) else name = file
header_name = name + '.hdr'
get_lun, hdr
openw, hdr, header_name

s="
eol=bytarr(2)
eol[0]=byte(13)
eol[1]=byte(10)
writeu, hdr,'ENVI'
writeu, hdr, eol
writeu, hdr,'description = {IDL processing result}'
writeu, hdr, eol
s = 'samples = ' + string(samples)
writeu, hdr, s
writeu, hdr, eol
s = 'lines   = ' + string(lines)
writeu, hdr, s
writeu, hdr, eol
s = 'bands   = ' + string(bands)
writeu, hdr, s
writeu, hdr, eol
writeu, hdr,'header offset = 0'
writeu, hdr, eol
writeu, hdr,'file type = ENVI Standard'
writeu, hdr, eol
s = 'data type = ' + string(type)
writeu, hdr, s
writeu, hdr, eol
s = 'interleave = ' + inter
writeu, hdr, s
writeu, hdr, eol
writeu, hdr,'sensor type = Unknown'
writeu, hdr, eol
writeu, hdr,'byte order = 0'
writeu, hdr, eol
writeu, hdr,'y start = 1'
writeu, hdr, eol
s ="
if bandnames EQ " then begin
writeu,hdr,'band names = {
writeu,hdr,eol
for i=1,bands do begin
  is=string(i)
  is=strtrim(is,2)
  s=s+'Band'+is+','
endfor
pos=strlen(s)-1
strput, s,'}',pos
writeu,hdr,s
  writeu,hdr,eol
endif else writeu,hdr,bandnames
free_lun, hdr
end
APPENDIX TWO

Validation of the Spatial Statistic with Test Data

This section outlines the testing of the spatial statistic conducted by Dr Carl Menges. Development and validation of the spatial statistic was conducted in stages. Firstly, the statistic was applied globally using a large number of random samples in an artificially created “test” image and the results were compared to a semi-variogram. Secondly, the statistic was applied to a number of individual points within the image in order to develop a method for normalising the results. Lastly, from the normalised statistic an image was generated, which contains the suggested plot size for every pixel.

Test Image Data

The artificial test data was created using ENVI 3.5 test image generation functions and is shown in Figure A.2.1. The test patterns in images 1 to 4 contain circles of value 2.0 on a black (value 1.0) background. The circle diameter is 12, 12, 25, and 50 pixels for bands 1 to 4 respectively. Images 5 to 8 are the result of multiplying images 1 to 4 with a background of uniformly distributed noise in the range of 0.0 to 1.0 (using ENVI V3.5 test image generation with uniformly-distributed random numbers). Images 9 to 16 are a replicate of images 1 to 8, the only difference being, that the circles are not of a uniform value but were designed as a greyscale ramp with increasing brightness towards the centre.

Global Application of Statistic

The statistic was applied to the test pattern images globally by repeating the point calculation as outlined in Chapter 5 for 2000 random starting locations. The
semi-variogram was calculated for the same data using the classical estimator (Matheron 1963):

\[
2\gamma(h) = \frac{1}{|N(h)|} \sum (Z(x_i) - Z(x_j))^2
\]

where,

|N(h)| is the number of location pairs at distance h;

\(x_i\) and \(x_j\) are locations a distance \(h\) apart (the lag); and

\(Z(x)\) is the observed value of variable \(Z\) in location.
Figure A.2.1: Test patterns 1-16 used for testing the statistic.
The results of the statistic and the semi-variogram are shown in Figure A.2.2 ((A) and (B) respectively). For the test pattern in image 1, the statistic appears sensitive to the size of the circles. Very distinct minima appear at multiples of the circle diameter (12 pixels). The semi-variogram for this image exhibits maxima at these positions. This is not the case for the test pattern in image 2 indicating that the density of features affects the statistic. The semi-variogram for image 2 does not exhibit the periodicity but the range location can be clearly identified and coincides with the circle diameter. The increasing circle sizes in images 3 and 4 are not well characterised by the statistic either. The result for image 3, with a diameter of 25 pixels, has no clear minima, which may be a result of the distribution to which the statistic is sensitive. The range of the semi-variogram indicates this circle size accurately. The result for image 4 exhibits a minima at a lag of 30, despite the circle diameter being 50 pixels. The range of the semi-variogram indicates a feature size of 40, which is also unrelated to the circle diameter.

The results for the test patterns in images 5 to 8 exhibit a distinctively different shape due to the added noise background. While some indication of feature size is still present for image 5, the overall trend is towards a hyperbolic function and an indication of some structural feature between 15 and 20m pixels in size. The semi-variogram for these images indicates a large nugget value due to the noise, an indistinct range location and some periodicity for image 5. The random noise is dominating these data and obscuring the effects of the features present.

The effect of replacing the uniform circles by a greyscale ramp has the effect of reducing the magnitude of both statistical measures but retaining a great similarity in the sensitivity to features. The major difference is that the range location of the semi-variogram for images 9 to 11 has been reduced to that of images 1 to 3. That is, the feature size is now underestimated. The range location for image 12 remains unchanged. This may indicate that the semi-variogram for this image is largely
determined by high contrasts between the target and background rather than the gradient of circular features.

With the addition of noise in images 13 to 16, the semi-varioogram becomes virtually featureless indicating the virtual absence of any spatial correlation. The result of the statistic is similar to that obtained for images 5-8, but this time with structural features indicated between 10 and 20 pixels.

The results shown in Figure A.2.2 demonstrate that the statistic exhibits some sensitivity to the size and distribution of image features if applied globally. The semi-variogram appears to provide better definition for the clearly defined patterns, whereas the proposed statistic retains more informative detail for the test patterns containing random noise.
Figure A.2.2: Global calculation of the standard deviation from the statistic (A) and the semi-variogram (B) applied to test patterns 1-16.
Local Application and Normalisation

The resulting standard deviation values for the statistic being applied to the centre points of the features in the test images are shown graphically in Figure A.2.3. The result for the test patterns in images 1, 3 and 4, which consist of uniform circles with varying diameter on a uniform background, exhibit a standard deviation of zero for small window sizes as the averages within the window are equal when displaced by the error margin of one pixel. A maximum value is reached when the window size is equal to the circle diameter. The standard deviation then reaches a minimum and increases again when the window size is large enough to include a second feature. An adequate plot size for sampling the feature would have to be chosen before the first maximum is reached. The addition of noise to the test patterns in images 5, 7 and 8 changes the results considerably. The standard deviation for small window sizes is very large and the small maxima that can be observed for the uniform images is hardly visible due to this overall trend of diminishing values due to the increasing window size. The same phenomena can be observed for images 13, 15 and 16 where the features consist of a greyscale ramp and noise is present. The results for images 9, 11 and 13, which are free of noise show an increased standard deviation for small window sizes relative to the uniform features and the associated maxima are obscured.
Figure A.2.3: Standard deviation form of the statistic from local scale application to the centre points in test patterns 1-16.

The graphical results for images 13, 15 and 16 in Figure A.2.1, which most closely approximate a natural environment with the presence of noise and non-uniform features are enhanced in Figure A.2.4.

The left side of Figure A.2.4 shows the standard deviation graphs for test pattern images 13, 15 and 16 with a reduced y-axis to depict smaller variations in the standard deviation range. The maxima seen for the results of the uniform images can be recognised here as deviations from the overall hyperbolic shape. For image 13, there appears to be a minimum at a lag of 9. For image 15 a minimum at lags 6 and 9 can be seen and for image 16, there is a minimum at lag 4. These, however, are difficult to interpret in their significance. To remove the overall trend from the standard deviation graphs and enhance the observed fluctuations, the data were
normalised against the global statistic for each respective test pattern image using a normalised ratio. The results are shown on the right hand side of Figure A.2.4 for the same images. The minima and maxima can now be seen very clearly and the significance is indicated by the actual value. Values below zero exhibit a lower level of variation than the global average for the same window size. For image 13, the minimum at a lag of 9 is negative and can be interpreted as an ideal plot size. However, this equates to a window size of 19x19, which is larger than the feature size. To sample a feature of such large internal variation relative to the global average, therefore, one must incur a large sampling error if no sufficiently large feature can be found to accommodate the required plot size. The same plot size is indicated for images 15 and 16. This is not surprising as the images only differ in feature size but not texture. For these images the feature size would be sufficient to accommodate the suggested plot size. The minimum at a lag of 4 indicated for image 16 is still visible but it has a positive value suggesting that the internal variation is not minimised. This could also be expected as the background within the features was enhanced relative to the background by the multiplication with a value larger than one.
Figure A.2.4: Normalised standard deviation form of the statistic from local scale application to the centre points in test patterns 13, 15 and 16.

Generating an Image of Appropriate Plot Size

The statistic was used to generate an image from the application of the normalised statistic to every image element (with the exception of edges, where the maximum window size can not be generated). The maximum window size was limited to a lag of 15 and the value recorded in the generated image was the lag at
which the statistic first assumes a negative value. The result was colour coded to enhance the difference in values and is shown in Figure A.2.5.

For all images, the lowest values, that is the smallest suggested plot sizes for sampling (with a single pixel registration error between image and field data) the feature, are located in the centre of the large uniform circular features (images 3 and 4). The largest values are located at the boundaries of the features with higher values for definite boundaries. For the smallest circular features in the images containing noise, there is no plot size indicated, that does not exceed the feature size, confirming the previous result. In the images with larger non-uniform features (images 11 and 12) the optimum plot location is at the centre. Where the value indicates a plot size that encompasses the largest possible area of this feature considering that there is a one pixel error margin. The comparable uniform features (images 3 and 4) suggest the smallest window size as there is no variation present. The images containing noise are a better simulation of a natural environment and the complexity increases accordingly. For test patterns derived in this manner from the uniform features (images 7 and 8), the centre areas are still indicated as the most suitable location with a lag of four to seven. For images 15 and 16, where the features are derived from the graded greyscale features, individual features are now shown as distinctly different. Most circles in image 16 could be sampled at specific locations with a lag as low as 4 to minimise the sampling error due to locational uncertainty. The proportion and distribution of the suggested plot sizes varies greatly between the different features.
Figure A.2.5: Image generated from the application of the normalised statistic to test patterns 1-16.
APPENDIX THREE

Calculation of Coefficients and Analysis of Fit for Non-Linear Regressed Biomass (t/ha) vs Backscatter Intensity

The following is the source code for a program written in Mathematica (V4.1). The program uses biomass values (t/ha) and SAR backscatter (Intensity), which are fitted to a standard hyperbolic function, to examine saturation effects of the SAR signal.

Program Calculation of Coefficients and Regression Analysis of Fit

Calculation of coefficients and regression analysis of fitting

\[-\frac{a}{(x-b)} + c = y\]

(Where: \(x = \text{Biomass (tonnes per hectare)}\), \(y = \text{SAR backscatter (intensity)}\), \(a\), \(b\) and \(c\) are parameters)

Data input order:
Biomass (t/ha)
Backscatter (Intensity)

Data 1= (Input data from prepared spreadsheets)

Needs ["Statistics ‘NonlinearFit’"]

NonlinearFit[data1, -a/(x1-b) + c, {x1}, {a, b, c}, MaxIterations->10000]

NonlinearRegress[data1, -a/(x1-b) + c, {x1}, {a, b, c}, MaxIterations->10000]
Figure A.4.1: Location of Mary River Floodplain System sites surveyed for biomass estimation indicated as cyan points (displayed on a Landsat ETM image. RGB: 5,4,3).
Figure A.4.2: Location of Trans Fly sites surveyed for biomass estimation and used in regression analysis, indicated as cyan points (displayed on a Landsat ETM composite image. RGB: 5,4,3).