

The potential of airborne polarimetric synthetic aperture radar data for quantifying and mapping the biomass and structural diversity of woodlands in semi-arid Australia.

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## THE POTENTIAL OF AIRBORNE POLARIMETRIC SYNTHETIC APERTURE RADAR DATA FOR QUANTIFYING AND MAPPING THE BIOMASS AND STRUCTURAL DIVERSITY OF WOODLANDS IN SEMI-ARID AUSTRALIA

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## Abstract

Levels of carbon dioxide in the atmosphere have been steadily increasing since the beginning of the Industrial Revolution in the 1800s. The earth's climate is sensitive to alterations in these levels of carbon dioxide and other greenhouse gases (GHG), with significant changes in climate predicted long term. The adoption of the Kyoto Protocol in 1997 heralded a new age in terms of greenhouse gas accounting and emissions responsibility, for all nations. In Australia, carbon emissions from the Land Use and Land Use Change and Forestry sector are responsible for a large proportion of the national total emissions. Radar remote sensing has demonstrated considerable potential in the estimation and mapping of vegetation biomass and subsequently carbon.

The aim of this research is to investigate the potential of airborne polarimetric radar for quantifying and mapping the biomass and structural diversity of woodlands in semi-arid Australia.

Initial investigation focussed on the physical structure of the woodland, which revealed that despite a diversity of woodland associations, the species diversity was relatively low. Both excurrent and decurrent growth forms were present, which subsequently resulted in varying allocation of biomass to the components (i.e., branches, trunks).

In view of this, both empirical and modelling methodologies were explored. Empirical relationships were established between SAR backscatter and the total above ground biomass. Considerable scatter was present in these relationships, which was attributed to the large range of species and their associated structures. Comparison of actual and model simulations for C-, L- and P-band wavelengths, reveal that no significant difference existed for these wavelengths, except at CHH, and the cross-polarised data at L- and P-band.

The study confirmed that microwaves at C-band interacted largely with the leaves and small branches, with scattering at VV polarization dominating. Compared to the lower frequencies, the return from the ground surface (as expected) was significant. The differences in scattering mechanisms (i.e., branch-ground versus trunk-ground) between excurrent and decurrent structures were due largely to the larger angular branches associated with Eucalyptus and Angophora species, which were absent from *Callitris glaucophylla*.

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# Glossary

#### ACRONYMS

AIRSAR	Airborne Synthetic Aperture Radar
AGO	Australian Greenhouse Office
ALOS PALSAR	Phased Array type L-band Synthetic Aperture Radar
AMG	Australian Map Grid
API	Aerial Photography Interpretation
BA	Basal Area
BAF	Basal Area Factor
BL	Branch Length
BM	BioMass
BRS	Bureau of Rural Sciences
CA	Crown Area
CASI	Compact Airborne Spectrographic Imager
CCD	Charge Coupled Devices
CLD	Canopy Layer Depth
СОР	Conference of Parties
CPC	Canopy Projected Cover
CSIRO	Commonwealth Scientific Investigation Research
	Organisation
CTIC	Cross Track Illumination Correction
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
DN	Digital Numbers
DNRM	Department of Natural Resources and Mines
DOB	Diameter Over Bark
DPI	Department of Primary Industry
DTM	Digital Terrain Model

DUB	Diameter Under Bark			
ELC	Empirical Line Calibration			
ENSO	El Nino Southern Oscillation			
ENVI	Environment for Visualising Images			
ENVISAT ASAR				
ERS	European Remote Sensing Satellite			
ETM+	Enhanced Thematic Mapper Plus			
FPC	Foliage Projective Cover			
GCP	Ground Control Points			
GHG	GreenHouse Gas			
GIS	Geographic Information System			
GPC	Ground Percent Cover			
GPP	Gross Primary Productivity			
GPS	Global Positioning Satellite			
GSC	Ground Surface Cover			
GWC	Gravimetric Water Content			
НҮМАР	Hyperion Mapper			
INS	Inertial Navigation System			
IPCC	Intergovernmental Panel on Climate Change			
IS	Importance Sampling			
JAXA	Japanese Aerospace Exploration Agency			
JERS	Japanese Earth Resources Satellite			
JPL	Jet Propulsion Laboratory			
LIDAR	Light Detection And Ranging			
LSP	Large Scale Photography			
MSS	Landsat Multispectral Scanner			
NASA	National Aeronautical and Space Administration			
NASDA	National Space Development Agency of Japan			
NCAS	National Carbon Accounting System			
NDVI	Normalised Difference Vegetation Index			
NIR	Near Infra Red			
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NGGI	National Greenhouse Gas Inventory			
NPP	Net Primary Productivity			
NPPA	Net Primary Productivity (Above-ground)			
NPPB	Net Primary Productivity (Below-ground)			
NSW	New South Wales			
OECD	Organisation for Economic Cooperation and Development			
PACRIM	Pacific Rim			
PDF	Probability Density Function			
PIF	Pseudo-Invariant Feature			
POLSAR	Polarimetric SAR			
POS	Position and Orientation System			
PPP	Primary Photo Plots			
PSU	Primary Sampling Unit			
PVC	Poly Vinyl Chloride			
QLD	Queensland			
QLDDNRM	Queensland Department of Natural Resources and Mines			
RADARSAT	Canadian Radar Satellite			
RBS	Randomised Branch Sampling			
RGB	Red Green Blue			
RMS	Root Mean Square			
RSD	Residual Standard Deviation			
SAR	Synthetic Aperture Radar			
SBB	Southern Brigalow Belt			
SID	Stem IDentification			
SW	Sapwood Width			
SIR-A	Shuttle Imaging Radar (flown in 1981)			
SIR-B	Shuttle Imaging Radar (flown in 1984)			
SIR-C	Shuttle Imaging Radar (flown in 1994)			
SLATS	Statewide Landcover And Trees Study			

SSU	Secondary Sampling Unit
SSDx	Sum of Squares of the Deviations in x
SWIR	Short Wave Infra Red
TAGB	Total Above Ground Biomass
TBC	Tropical Beef Centre
TDR	Time Domain Reflectometer
TID	Tree IDentification
TIN	Triangular Irregular Network
TLD	Trunk Layer Depth
ТМ	Thematic Mapper
TOPSAR	Topographic SAR
UNEP	United Nations Environment Programme
UNFAO	United Nations Food and Agricultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
UNSW	University of New South Wales
UTM	Universal Transverse Mercator
VWC	Volumetric Water Content
WGS	World Geodetic System
WMO	World Meteorological Organisation

# SYMBOLS, PARAMETERS AND UNITS

Α	Area of vegetation
A <sub>L</sub>	Leaf Area
As	Sapwood Area
BL <sub>tot</sub>	Branch Length Total
BLs	Small Branch Length
BL <sub>1</sub>	Length of Branches >1cm
B <sub>n</sub>	SAR backscatter from non-forest

Bs	Average Volume of the Stem; SAR backscatter from forest
B <sub>ST</sub>	Volume of the Stand
B <sub>T</sub>	Total Biomass
c	Speed of electromagnetic radiation
CD <sub>CB</sub>	Crown Depth to Crown Base
CD <sub>FLB</sub>	Crown Depth to First Leafing Branch
Crown_EW	Crown diameter (east-west direction)
Crown_NS	Crown diameter (north-south direction)
CT	Total Carbon
D <sub>30</sub>	Diameter at 30cm
D <sub>130</sub>	Diameter at 130cm
dB	Decibels
EXP	Probability density function exponent
F	Fractional polarisation
F	Form Factor
G <sub>DEM</sub>	Height of the vegetation returns above the ground surface
Gg	Gigagrams
GHz	Gigahertz
h	Altitude of the aircraft
i	Line number of the object in the image
ha	Hectare
HH	Horizontally transmitted and Horizontally received radar
	wave
HTTOP	Height of Tree
HT <sup>flb</sup>	Height of Tree to First Leafing Branch
HV	Horizontally transmitted and Vertically received radar wave
Ka	Dielectric constant
Kg	Kilogram
Kt	Kilotonne
La	Antenna length

Μ	Carbon Mass
MA	Carbon Mass per Unit Area
Mg	Megagrams
MHz	Megahertz
n	Index of Refraction
ns	Number of stems per hectare
P <sub>min</sub>	Minimum received power
P <sub>max</sub>	Maximum received power
Ppmv	Parts per million by volume
$\Delta \mathbf{p}$	Degree of polarisation
R <sub>0</sub>	Near range (m)
$\Delta R_0$	Slant range (m)
R <sub>s</sub>	Energy used in respiration
S	Scattering matrix
t	tons
ТР	Total Power
V	Coefficient of Variation
v	Frequency of the electromagnetic wave
$V_{\rm f}$	First return from vegetation
$V_1$	Last return from vegetation
Vs	Stem Volume in cubic metres
VV	Vertically transmitted and Vertically received radar wave
W	Water content of Soil
Wa	Antenna width
Wg	Swath width
$W_{w}$	Soil wet weight
W <sub>d</sub>	Soil dry weight
β	Regression coefficient for height class
$\sigma^{\circ}$	Backscattering coefficient
χ	Ellipticity

α	Attenuation coefficient
χn	Tree height class
φ	Branch angle orientation (°)
ε'	Real part of dielectric constant
ε''	Imaginary part of dielectric constant
ε	Permittivity of the real surface
ε <sub>0</sub>	Permittivity of the free space
ε <sub>r</sub>	Relative permittivity (or dielectric constant)
λ	Wavelength of electromagnetic radiation
θ	Incidence angle
φ	Phase difference
γ	Orientation
$ au_{\mathbf{p}}$	Pulse length
μ	Magnetic component of dielectric constant
ρ	Surface reflectance (%)

# SPECIAL NAMES

$CO_2$	Carbon dioxide		
CO <sub>2</sub> -e	Carbon dioxide equivalent		

# Chapter 1 Introduction

### 1.1 Overview

As a signatory to the 1992 United Nation's Framework Convention on Climate Change (UNFCCC), Australia was obliged to produce an annual National Greenhouse Gas Inventory (NGGI). In 1996, the first NGGI revealed that for 1990, net carbon emissions were ~400 Mt CO<sub>2</sub> \_equivalent, with an unexpected 21 % (i.e., 107 Mt CO<sub>2</sub>) associated with the Land Use, Land Use Change and Forestry (LULUCF) sector (Keenan 2002). To estimate emissions from Land Use Change (LUC), the NGGI calculated carbon losses as the product of the area of vegetation cleared and the above ground biomass of the cleared vegetation. The area of clearing was estimated originally using time-series of Landsat sensor data and local knowledge. Three estimates of the above ground biomass of cleared vegetated were used, with these relating to open (~ 21 Mg ha<sup>-1</sup>), medium (~ 60 Mg ha<sup>-1</sup>) and tall forests (~100 Mg ha<sup>-1</sup>).

In 2000, a second NGGI was produced which revealed lower emissions of carbon (38.0 Mt CO<sub>2</sub>-equivalent) from the LUCUCF sector, representing 7.1% of the net national emissions and a dramatic reduction, compared with 85.9 Mt in 1990 (AGO 2002a). This reduction was, in part, due to differences in the values of above ground biomass allocated as land clearing had actually increased. In addition, attention focused on the thickening of woody vegetation (Australian State of the Environment Committee 2001) which, in the state of Queensland alone, currently provides a sink in excess of 27 Mt C/yr above ground (Burrows *et al.* 1998). Post 2002, rates of clearing continue to be high (although declining) within Australia, particularly in Queensland, but are still contributing a substantial proportion of emissions. The current net estimates of land clearing

emissions (18.6 Mt C y year<sup>-1</sup>) include 23.5 Mt C year<sup>-1</sup> of gross emission and 4.9 Mt C year<sup>-1</sup> of removals in regrowth following past clearing (Keenan 2002).

Despite publication of these emissions, there is still uncertainly attached to the estimates of the area of land cleared and regenerating but particularly the biomass (carbon) contained within the vegetation cleared or sequestered annually through natural regeneration or replanting. In the past, estimates of vegetation biomass have been based largely on plot measurements, obtained for selected forest and woodland types or on local knowledge. More recently, relationships between surrogates of biomass (e.g., basal area) and remotely sensed optical data have been used to better account for spatial variability in biomass (Lucas *et al.* 2000b, Austin *et al.* 2002). However, few techniques have been able to produce estimates that can be used with confidence.

For these reasons, and in this research, the use of airborne Synthetic Aperture Radar (SAR) for quantifying the biomass of woodland vegetation in Queensland is investigated as an alternative for generating regional estimates. SAR has shown promise worldwide for estimating biomass but has rarely been used in Australia. However, with the NASA JPL AIRSAR PACRIM Mission to Australia in 2000, an opportunity for evaluating the potential of these data became available. During the Mission, four flight lines of fully polarimetric AIRSAR data, together with other remote sensing and field data, were acquired over an area of mixed species woodlands near Injune in central Queensland. This area has been a hotspot for vegetation clearing in the State. This thesis documents the research undertaken to evaluate the use of these data for quantifying the biomass and also the structural diversity of these woodlands.

In Chapter 1, the reasons for the study are outlined, with attention focusing first on the global situation regarding greenhouse gas emissions and climate change. A brief history of international agreements aimed at reducing emissions is also

provided. Vegetation clearance prior to and post European settlement in Australia and the most recent clearing statistics for Australia and also Queensland are reviewed and environmental impact stated. Methods for retrieving land use change information and biomass are presented in more detail. Finally, the aims and a general overview of the research are given and the content of the remaining chapters of the thesis is outlined.

### 1.2 Greenhouse gas emissions and climate change

Prior to the industrial revolution, atmospheric levels of carbon dioxide (CO<sub>2</sub>) were maintained at approximately 280 ppm but since the mid 1880s, levels have increased exponentially with currently recorded levels exceeding 360 ppm (Corfee-Morlot and Hohne 2003). These increases can be attributed almost entirely to human activity, particularly since the Industrial Revolution.

### 1.2.1 Human impacts on vegetation: Past and present

The influence of man on the levels of greenhouse gases commenced with the expansion of agriculture. For centuries, vegetation has been cleared by the original inhabitants of Australia, America and Africa using fire. As early as 500 AD, large areas of forest and woodland in Europe had started to be permanently removed using basic tools such as stone axes and fire (Goudie 1986). Much of the land was used for cereal cultivation and in several European countries (e.g., Britain), there were as many people farming during the Iron Age as there were in the early 1900s. Through these processes, carbon was released from biological storage largely through the processes of vegetation decomposition and burning.

This early clearing had little impact on the levels of atmospheric  $CO_2$ . However, in the mid 1800s, the Industrial Revolution heralded the beginning of elevated levels of  $CO_2$  as fossil fuels, such as coal, oil and natural gas were combusted to support increasing demand for energy (e.g., heating, transport and electricity). At the same time, the human assault on the environment became more aggressive and, following the Industrial Revolution, clearance of vegetation became widespread. These factors combined also led to a rapid and exponential increase in the levels of methane ( $CH_4$ ) and nitrous oxide ( $N_20$ ) in the atmosphere.

### 1.2.2 CO<sub>2</sub> and climate change

Changes in atmospheric CO<sub>2</sub> associated with anthropogenic activity were revealed initially in deep ice core records from Stiple Station in Antarctica, which established a steady increase from  $280 \pm 5$  ppmv from the 1970s. Since 1958, measurements at four 7 m towers and one 27 m tower on Mauna Loa in Hawaii have routinely registered an increase in atmospheric CO<sub>2</sub> and these have been confirmed by similar measurements acquired at Cape Grimm in Tasmania. The atmospheric concentration of CO<sub>2</sub> is currently increasing exponentially at around 0.5-3ppmv per year (Keeling and Whorf 2001), with current levels estimated at 360ppmv (Corfee-Morlot and Hohne 2003).

The implications of increasing  $CO_2$  concentrations are now being realised. Greenhouse Gases (GHG) in the atmosphere are largely transparent to incoming short wave solar radiation, but absorb much of the longer wave energy emitted by the Earth's surface. As a result of this radiation trapping, warming of the atmosphere and the Earth's surface has occurred. Since the beginning of the 20<sup>th</sup> century, an increase of 0.6 ± 0.2 °C has been observed (IPCC 2001). The IPCC predicts that by the year 2100, the globally averaged surface temperature will warm by 1.4-5.8°C, relative to 1990 (AGO 2002b). Such temperature changes are impacting on local, regional and global climate and leading to disruption of natural ecosystems, particularly those that have limited adaptive capacity and are therefore vulnerable to climate change. Ecosystems that are particularly affected include coral reefs and atolls, tropical forests and mangroves and alpine and polar environments, although few are immune. The impacts of climate change range from increases in species abundance and changes in their geographical extent to extinction of others. Human systems are equally

vulnerable, particularly those that depend on water resources such as agriculture, forestry and fisheries.

### 1.3 Climate Change and International Agreements

In 1988, the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in response to growing concerns surrounding global climate change. The role of the IPCC was to assess the scientific, technical and socio-economic information relevant for the understanding of the risk of humaninduced climate change. Since its formation, the IPCC has been instrumental in negotiations surrounding the formation of the United Nations Framework Convention on Climate Change (UNFCCC) and the adoption of the Kyoto Protocol.

The centrality of greenhouse gas emissions to issues relating to deleterious climate change and the subsequent threat to the global environment prompted the adoption of the UNFCCC. The convention was drafted in 1992 and has since been ratified by 174 countries. The UNFCCC was particularly successful as it articulated global concerns regarding continuing increases in GHG emissions and encouraged developed nations to also address ways of reducing emissions. The UNFCCC did not contain any binding emission reduction targets. However, it did oblige signatory countries to quantify national emissions in 1990 and to quantify, on an annual basis, changes in these emissions.

In December, 1997, the 170 countries at the Third Conference of the Parties (COP-3) to the UNFCCC unanimously adopted the Kyoto Protocol. In contrast to the original agreement, the Protocol contained legally binding targets for GHG emission reductions of 5.2 % relative to 1990 levels during the first 5-year commitment period from 2008 to 2012. As well as significantly strengthening commitments contained in the UNFCCC, the Protocol also provided special consideration to carbon emissions from the LULUCF sector. However, the Kyoto

Protocol can only become legally binding following ratification by at least 55 Parties to the UNFCCC, including industrialised countries whose emissions represented at least 55 % of the total 1990 emission from the group.

Despite early successes, the conclusion of climate change negotiations in the Hague (COP6) in November 2000, witnessed several key players, namely the United States, Australia and Japan, remaining intransigent on the ability of the Protocol to actually reduce greenhouse gas emissions even though it was anticipated that implementation of the treaty would be achieved. These reactions heralded the dawn of disquiet with respect to the future of the Protocol, with the withdrawal of the United States from negotiations in March, 2001. To date, only 60 countries have ratified including the United Kingdom (UNFCCC 2003). In November, 2001, COP7 witnessed the finalisation of the operational details (e.g., penalties faced by countries failing to reach the targets) and, in doing so, opened the way for the widespread ratification by governments at COP8 in October, 2002. Of the larger industrialised nations whose emissions represented at least 55 % of the total 1990 emissions, Canada was the last to ratify the Protocol in December 2002 and Australia has withdrawn. As of COP9 in December 2003, Russia has announced that they will not ratify the protocol. Consequently, many believe the Kyoto Protocol is "dead". However, it may more accurately be in a state of "dormancy", since debate within Russia's government about whether to ratify, should be expected.

#### 1.4 Land Use, Land Use Change and Forestry (LULUCF).

A key sector for which calculations of GHG emissions are required is the LULUCF sector. Within this sector, the distribution of carbon pools and mechanisms for release (sources) and uptake (sinks) are considered in some detail, both within the UNFCCC and the Kyoto Protocol. In particular, GHG emissions and removals are calculated from a number of activities (e.g., afforestation, deforestation and reforestation or ARD under Article 3.3 of the Kyoto Protocol). Additional activities may also be accounted for (e.g., under Article 3.4 of the same agreement), such as forest management, cropland management and revegetation (NCAS 2002). The following sections outline these changes in more detail.

### 1.4.1 Changes in forest and woody biomass stocks.

Forest is defined in the Marrakech Accords, as a minimum area of land of 0.05-1.0 hectares with tree crown cover, or equivalent stocking level, of more than 10-30 % and containing trees with the potential to reach a minimum height of 2-5 m at maturity. Within many countries, including Australia, woodlands are also encompassed within the forest definition. Areas that are "temporarily" below the thresholds applied but which are expected to grow or revert to forest, such as plantations, harvested areas and young natural stands, are also included under the forest category (Rosenqvist *et al.* 2003). Changes in forest and their woody biomass stocks occur largely as a result of deforestation or regeneration.

Under the UNFCCC and the Kyoto Protocol, deforestation is regarded as the direct human-induced conversion of forested to non-forested lands with the amount of carbon released through deforestation depending largely on the biomass (both above and below ground) of the vegetation affected. Globally, the above ground biomass of vegetation approximates 31 Mg ha<sup>-1</sup>. However, undisturbed tropical forests generally support biomass levels that are greater than 200 Mg ha<sup>-1</sup> (Imhoff 1995b) and losses through clearing can be particularly high. Indeed, as much as 30 % of the additional burden of CO<sub>2</sub> in the

atmosphere has been contributed by tropical deforestation (Fearnside and Guimaraes 1996). In northern hemisphere temperate and boreal forests, the average above ground biomass is lower (~ 150 Mg ha<sup>-1</sup>). Much of the woodlands, savannas and shrub lands that cover more than one quarter of the global vegetated land surface (Asner *et al.* 1997) are contained largely within the subtropical regions of Africa, Australia, Asia and South America, and these support a biomass averaging ~ 30 Mg ha<sup>-1</sup>. However, in all regions, the biomass of forests is spatially variable as a result of environmental conditions and human activities. In particular, forests in many regions are at various stages of regeneration, largely as a result of human activity, and their biomass is generally lower than that of the mature stands. However, these regenerating forests are also subject to clearance, although associated emissions of GHG are clearly lower compared to when more mature forests are cleared.

In most cases, the carbon contained within the woody biomass is assumed to be lost immediately through the process of deforestation. When vegetation is burned, losses are certainly immediate. However, many forests are cleared without the use of fire or may be left standing (e.g., trees that have been ring barked or poisoned) but dead. In these cases, the loss of carbon may take place over several decades or even centuries through the more gradual process of decomposition. Wildfires may also lead to natural loss of carbon, which may be substantial. In northern Australia, for example, an estimated 80 Mt of CO<sub>2</sub> per year is released annually through savannah fires, which is more than that released through the transport sector (70 Mt) and LULUCF activities (Australian State of the Environment Committee 2001).

Despite significant loss of carbon from deforestation, regenerating vegetation worldwide is generally regarded as being a sink for carbon, including that lost previously through deforestation. In the Amazon Basin alone, over 37 % of deforested lands are regenerating (Lucas *et al.* 2002). In several tropical countries,

all forests are regarded as secondary and now represent a major economic resource. As most regenerating forests are recovering from previous (and often recent) clearance, the majority are relatively young and are rapidly accumulating carbon. In some savannas and woodlands, vegetation thickening appears to be extensive, largely as a result of changes in fire and management regimes and has been associated with a significant carbon sink (Burrows *et al.* 1998).

Although a significant proportion of the World's forests are in regeneration, only a proportion can be included in national carbon accounting processes. Specifically, Article 3.3 of the Kyoto Protocol states that only carbon sinks associated with afforestation and reforestation could be included, although some consideration was given to forest management activities. Afforestation is the direct human-induced conversion of land that has not been forested for a period of at least 50 years, while reforestation implies conversion of land that once was forested, but that had been converted to non-forested land. For the first commitment period, reforestation activities are limited to reforestation occurring on those lands that did not contain forest on 31st December 1989.

### 1.4.2 Forest and grassland conversion

Forests and grasslands play a significant role in the global carbon cycle, primarily due to their vast areas and subsequent carbon storage capacity. In forests, the vegetation biomass is the primary source of carbon storage; however, for grasslands a greater proportion of the carbon is stored in the soil.

### 1.4.3 Soil modification

The flux in soil carbon as a result of land use change is also a fundamental consideration in assessing present day GHG emissions. As mentioned in Section 1.4.2, the conversion of forest and grassland results in substantial  $CO_2$  emissions. The soil is a significant contributor to these emissions, since the destruction of forest and the conversion of grassland to arable farmland impacts on the biophysical properties of the soil. For example, ploughing of the soil, followed by

the sowing and harvesting of crops, results in enhanced oxidation of organic matter, which is subsequently emitted into the atmosphere as CO<sub>2</sub>. Increased aeration and temperature of the soil during and following tillage also impacts on the physical and chemical properties of the soil. In the tropics, for example, clearance of vegetation followed by cultivation or site preparation for tree planting may result in large decreases in soil carbon by up to 30-50% over a period of several decades (Fearnside and Barbosa 1998).

### 1.5 Vegetation clearance in Australia.

Australia's NGGI for 1990 gave the first indication of the extent of vegetation clearance in Australia at a time when most developed countries were observing stable or reduced levels. However, human impacts on vegetation have been occurring for centuries, although active clearance occurred and accelerated rapidly following European Settlement. The following sections provide a brief history of man's impact on vegetation in Australia.

### 1.5.1 Historical trends in vegetation clearance

Vegetation clearance in Australia has been ongoing, even prior to European settlement. The aborigines have inhabited the continent for approximately 40,000 years and were unevenly distributed, with the largest populations occurring along the south-eastern coastlines and the Murray River. Fire was widely used to increase the productivity of the land, thereby assisting activities such as hunting, although burning was generally controlled and directed (Kohen 1995). The impact of this burning on the vegetation is still a topic of debate although it has been suggested that forests were gradually replaced by open woodland and grasslands with both fire-dependent and fire-resistant communities predominating. Even so, prior to European settlement, a large proportion of the continent maintained a relatively natural distribution of vegetation (Figure 1.1).

In the semi-arid zone of Australia, the cessation of Aboriginal burning following European settlement led to a dramatic increase in the growth of woody weeds which subsequently replaced the grassland communities. As a result, these semi-arid areas became host to a different range of plant species. Indeed, Kohen (1995) suggested that the generation and sustainability of grasslands and woodland communities was largely an artefact of human activities. As well as increasing woody weed growth, the arrival of Europeans signalled the clearing of large areas of native vegetation.

At the time of European arrival in the late 1700s, woodlands (20-50 % crown cover), open forest (51-80 % crown cover) and closed forest (81-100 % crown cover) together with natural grasslands, shrublands and non-vegetated areas were extensive (Table 1.1). Clearance of these woodlands was undertaken largely to establish and expand agriculture in its myriad forms with much occurring preferentially on the plains, on the lower slopes of hilly areas and in fertile valleys, particularly those in the south east of the continent. In many areas, only remnants of the woodlands occur, with these restricted mainly to rocky areas, upper slopes of hills and areas subject to frequent inundation (e.g., alluvial plains). Heath and the low closed forests and closed shrublands were most impacted by clearance since European settlement, with only just over half of their original area remaining (Figure 1.2; Table 1.1 and 1.2).

The reasons for clearing vegetation varied within and between States. Much of the woody vegetation was removed within the Intensive Land Use Zone (ILZ) of Australia (Figure 1.3; Table 1.3) to allow livestock grazing, although large areas were used subsequently for production of agricultural crops, namely wheat. The variations in crops on land under cultivation varied over time and also by State and Territories. For example, clearance between 1861 and 1902 in Queensland was largely for maize production (Figure 1.4). Up to 1928, the primary crops varied between maize and grain but after 1928, production

focused mainly on wheat. In NSW, wheat was the main crop between 1861 and 2000 (ABS 2001). The grazing of sheep and cattle necessitated the continued clearing of vegetation. In Queensland, sheep numbers since 1885 have fluctuated greatly but tended not to rise progressively due to a number of factors such as drought, war and the depression (Figure 1.5a). However, cattle numbers have increased from 4.2 million in 1885 to 11.8 million in 2000 (Figure 1.5b). Despite the overall increasing trend for cattle, their numbers have been impacted by drought events on many occasions (e.g., the drought of 1904-05) and by the economic climates, both nationally and internationally.

Based on 1997 figures from the 2001 NLWR Audit, 17.6% of Queensland's total area has been impacted by clearance. Those vegetation types most significantly affected, in terms of area have been the eucalypt open forest, the eucalypt woodlands and the acacia forest and woodlands (Table 1.4).

Major vegetation group	Pre- European km²	Present (circa 1997) km <sup>2</sup>	Proportion remaining %
Rainforest and vine thickets	43,493	30,231	70
Eucalypt tall open forests	44,817	30,129	67
Eucalypt open forests	340,968	240,484	71
Eucalypt low open forests	15,066	12,922	86
Eucalypt woodlands	1,012,047	693,449	69
Acacia forests and woodlands	657,582	560,649	85
Callitris forests and woodlands	30,963	27,724	90
Casuarina forests and woodlands	73,356	60,848	83
Melaleuca forests and woodlands	93,501	90,513	97
Other forests and woodlands	125,328	119,384	95
Eucalypt open woodlands	513,943	384,310	75
Tropical eucalypt woodland/grasslands	256,434	254,228	99
Acacia open woodlands	117,993	114,755	97
Mallee woodlands and shrublands	383,399	250,420	65
Low closed forests and closed shrublands	15,864	8,749	55
Acacia shrublands	670,737	654,279	98
Other shrublands	115,824	98,947	85
Heath	47,158	25,861	55
Tussock grasslands	589,212	528,998	90
Hummock grasslands	1,756,962	1,756,104	100
Other grasslands, herblands, sedgelands and rushlands	100,504	98,523	98
Chenopod shrubs, samphire shrubs and forblands	563,389	552,394	98
Mangroves, tidal mudflats, samphires and bare areas, etc.	112,063	106,999	96

# Table 1.1Area of pre-european and present native vegetation in 2001<br/>(Source: NLWR 2001a)

Table 1.2Estimates of vegetation cover types (and % of total) in Australia in<br/>2003 (Source: NFI 2003)

Vegetation Type	Area (ha)	% of Total
Acacia	16488	10
Callitris	2330	1.4
Casuarina	2039	1
Eucalypt Mallee	12329	8
Eucalypt Woodland	76983	47
Eucalypt Open	37623	23
Eucalypt Closed	90	0.1
Mangroves	750	0.5
Melaleuca	7037	4
Other	2799	2
Rainforest	4214	3



Map of the extent of vegetation cover types in Australia prior to European Settlement (Source: NLWRA 2001a) Figure 1.1



1.1.



	NSW	Vic.	Qld	SA	WA	Tas.	NT	ACT	Aust.
Year	'000 ha.								
1870-71	156	280	21	235	22	64	-	-	868
1880-81	245	627	46	846	26	57	-	-	1,846
1890-91	345	822	91	847	28	64	-	-	2,197
1900-01	990	1,260	185	959	81	91	-	-	3,567
1910-11	1,370	1,599	270	1,112	346	116	-	-	4,813
1920-21	1,807	1,817	316	1,308	730	120	-	1	6,099
1930-31	2,756	2,718	463	2,196	1,939	108	1	2	10,184
1940-41	2,580	1,808	702	1,722	1,630	103	-	2	8,546
1949-50	2,295	1,881	832	1,518	1,780	114	-	4	8,424
1959-60	2,888	1,949	1,184	1,780	2,628	130	1	3	10,564
1969-70	4,999	2,212	2,208	2,290	3,912	98	6	2	15,728
1979-80	5,243	2,243	2,334	2,771	5,281	79	2	1	17,954
1990-91	4,073	2,063	2,872	2,933	5,359	75	6	-	17,382
1991-92	3,846	2,039	2,302	2,920	5,216	76	5	-	16,404
1992-93	3,906	2,258	2,316	3,073	5,668	73	4	1	17,297
1993-94	4,209	2,317	2,394	2,940	6,100	78	5	-	18,043
1994-95	3,432	2,296	2,056	2,991	6,182	77	4	-	17,040
1995-96	4,757	2,439	2,495	3,219	6,419	75	4	-	19,409
1996-97	5,589	2,552	2,685	3,279	6,950	73	5	-	21,133
1997-98	5,648	2,565	2,682	3,290	7,328	78	4	-	21,595
1998-99	6,173	2,749	3,014	3,648	7,597	76	7	-	23,264
1999-00	6,114	3,081	3,130	3,670	7,691	77	6	-	23,769

Table 1.3Area of crops in Australia, 1870-71 to 1999-2000 (ABS 2001)







Figure 1.4 Queensland crops produced between 1861-2000 (Source: Adapted from ABS 2001)



b)



Figure 1.5 Number of a) sheep and b) cattle in Queensland between 1885-2000 (Source: ABS 2001)

Major vegetation group	Pre-	Area	% of
	european	(circa 1997)	total
	(km²)	km <sup>2</sup>	
			extent
Cleared / modified native vegetation		304,043	17.6
Rainforest and vine thickets	30,055	19,558	1.1
Eucalyptus tall open forests	3,976	429	0
Eucalyptus open forest	62,646	35,150	2
Eucalyptus low open forest	111	111	0
Eucalyptus woodlands	473,272	367,293	21.2
Acacia forest and woodlands	182,089	91,534	5.3
Callitris forest and woodlands	5,601	4,134	0.2
Casuarina forest and woodlands	11,951	1,545	0.1
Melaleuca forest and woodlands	72,173	70,014	4
Other forests and woodlands	49,692	49,266	2.8
Eucalyptus open woodlands	165,065	134,421	7.8
Tropical Eucalyptus	20,684	20,653	1.2
woodland/grasslands			
Acacia open woodlands	39,861	36,734	2.1
Mallee woodlands and shrublands	14	14	0
Low closed forest and closed shrublands	449	445	0
Acacia shrublands	104,368	100,660	5.8
Other Shrublands	16,780	16,419	0.9
Heath	633	470	0
Tussock grasslands	294,662	282,547	16.3
Hummock grasslands	92,009	91,809	5.3
Other grasslands, herblands, sedgelands	4,963	4,771	0.3
and rushlands			
Chenopod shrub, samphire shrub and	82,070	81,944	4.7
forblands			
Mangroves, tidal mudflat, samphire and	15,442	15,143	0.9
bare areas, claypan, sand, rock, salt			
lakes, lagoons, lakes			

# Table 1.4Area of present vegetation groups in Queensland<br/>(Source: NLWR 2001a)

### 1.5.2 Near-recent clearance history

Despite increasing awareness of the adverse consequences of vegetation clearance (e.g., salinity, local to regional climate change, loss of biodiversity), large areas of native forests and woodlands in Australia continue to be being lost or degraded. Estimates of annual clearing rates were first available for the periods 1971-1980. These estimates (Table 1.5) were based on those derived from the National Greenhouse Gas Inventory (NGGI). The estimates revealed that most of the clearing was occurring in Queensland (886,257 ha) and NSW (428,151 ha). However, in comparison to Victoria and New South Wales, the widespread clearance in Queensland has only been very recent (Table 1.6).

The advent of satellite sensor observations over Australia, however, provided a far greater insight into the extent and also rate of clearing. Between 1991 and 1995, land clearing was assessed by comparing the extent of vegetation covers within 30 m spatial resolution Landsat Thematic Mapper (TM) data in the two years (Barson et al. 1998). This pivotal study revealed that over 337,350 ha had been cleared, with most activity occurring in Queensland (289,000 ha). Historical Landsat Multi-spectral Scanner System (MSS) data were subsequently analysed for the period 1981-1990 which revealed that over 550567 ha had been cleared in this period, with Queensland again reporting the highest rates (350,791 ha). In the assessment of clearance between1996 and 1999, rates of clearing increased to 424,444 ha yr<sup>-1</sup> with greatest losses occurring in Queensland (382,500 ha) and NSW (30,000 ha). For the period 1999-2001, the Queensland average annual clearing rate was 758,000 ha yr<sup>-1</sup>, which is 78% higher than the 1997-1999 average rate of 424,444 ha yr<sup>-1</sup> (QLD DNRM 2003). This high level of clearing in Queensland was largely responsible for the high contribution of the LULUCF to Australia's overall GHG emissions, as reported in the NGGIs.

State	1971-	1981-	1991-	1996-	2000
	1980	1990	1995	1999	
		Area Cl	eared (ha	year-1)	
NSW	428151	52232	19120	30000	100000
TAS	11817	2413	940	940	17000
WA	92464	92562	21150	3145	6000
SA	4171	28797	1370	2088	1600
VIC	21200	10766	2450	2450	2500
QLD	886257	350791	289000	382500	425000
NT	21094	12843	3320	3320	12700
ACT	-	163	-	-	0
Total	1465153	550567	337350	424444	564800
Australia					

Table 1.5Annual land clearing rates by state 1971-2000 (Source: ACF 2001)

Table 1.6	Extent of native vegetation clearance since European settlement- 2001
	(Source: NLWR 2001a)

State	Area (km <sup>2</sup> )	Cleared or Modified
New South Wales	234,527	30
Victoria	142,633	60
Queensland	304,043	18
South Australia	99,473	11
Western Australia	183,887	7
Tasmania	10,695	16
Northern Territory	6,055	_
ACT	738	31
Australia	982,051	13

As a result of this clearing, in 2000, Australia was placed in the unenviable position of being the sixth highest land-clearing nation in the world (UNFAO 2001), ranking with some of the most poorly developed nations of the world (Table 1.7). The UNFCCC's report on the in-depth review of the national communication of Australia (1995) maintained that 'improving the effectiveness and coverage of government controls on land clearing is the central approach to minimise  $CO_2$  emissions from this source'. Despite these recommendations, clearing of vegetation is still ongoing.

Country	Annual land	Country	Annual land
	clearing rate (ha)		clearing rate (ha)
Brazil	2226000	Malaysia	238000
Indonesia	1312000	Cameroon	222000
Sudan	959000	Venezuela	218000
Zambia	851000	Columbia	190000
Mexico	631000	Bolivia	161000
Australia	564000	Ecuador	137000
Dem. Republic of	532000	Angola	124000
the Congo			
Myanmar	517000	Paraguay	123000
Nigeria	398000	Ghana	120000
Zimbabwe	320000	Botswana	118000
Argentina	285000	Madagascar	117000
Peru	269000	Nicaragua	117000
Cote d'Ivoire	265000	Papua New	113000
		Guinea	
		Thailand	112000

Table 1.7Annual land clearing rate for countries clearing over 100000 ha per<br/>annum in 2000 (Source: UNFAO 2001)

### 1.6 Why Queensland?

In all assessment periods since the 1970s, Queensland has experienced the highest rates of clearing in Australia. Some reasons for this are outlined briefly in the following sections.

### 1.6.1 A history of clearing

Since settlement in the 1800s, agriculture has been the main resource base of Queensland and large areas of woodland have been cleared due to the development of this and other primary industries. With such development, grazing pressure, timber cutting, inappropriate fire regimes, vegetation poisoning and exotic weed invasion have all contributed to the loss and degradation of woodlands (Gifford and Howden 2001).

The advance of pastoralists and settlers into the Hunter Valley by 1825, served as a springboard for the invasion of the Queensland Brigalow Belt. In 1859, Queensland was separated from the "Mother Colony" and between 1870 and 1890, large areas of woodland were cleared to support an expanding agricultural industry with most occurring on the eastern margin on the Brigalow Domain. In this era, trees were felled using axes whilst the understorey was slashed with brush hooks. Following periods of drying, these large areas of felled 'Brigalow scrub' were torched (Nix 1994). With an estimated biomass of approximately 200-400 Mg ha<sup>-1</sup>, a substantial amount (albeit unquantified) of carbon was also released.

By 1900, railways had been constructed as far north as the Queensland border, providing agriculturalists in Queensland with access to the southern markets of NSW and Victoria and also an increased demand for their produce. The resulting requirements for high agricultural and pastoral production led to even further loss of woodland and large areas were cleared to support expansion of the beef industry and the introduction of cereal cropping. This was undertaken using axes and brush-hooks, as well as ring-barking.

Ringbarking is a process where the lower trunk of the tree is frilled with axe cuts, subsequently preventing the passage of water and nutrients from the soil to the foliage. The tree is left to decay and then often burnt, although trees may be left standing.

With the introduction of machinery in the 1960s, the capabilities for clearing large areas increased substantially. A common technique, that is still used today, was to harness a ship anchor chain, weighted by a large steel ball, between two large bulldozers and literally pull the woodland down, hence the term "pulling". This clearance was carried out in conjunction with burning. Using such techniques, an average of 1164 ha of woodlands was cleared daily between 1997 and 1999 (based on the clearing rate of 425,000 ha yr<sup>-1</sup>). In preparation for cultivated crops (e.g., wheat, oats, barley, canola and cotton), total clearance of the vegetation (and associated debris) was commonplace although for grazing, partial clearance was more typical.

The scale and rate at which vegetation can be cleared is far greater now due to the availability of modern machinery. Clearing has also been promoted in recent years by the proposed passing of laws limiting vegetation clearance. This, in effect, led to widespread 'panic clearing'.

### 1.6.2 Political impacts

The reasons for recent clearing and the location of clearing can be attributed partly to past ownership of the land and also State and Federal government policy. Within Queensland, 91 % of the total land area is under private tenure. Of this area, crown leasehold land occupies 60 % whilst the remaining 40 % is freehold land. The freehold tenure was applied typically to the most productive ecosystems. As a result, clearance has been more uncontrolled with over 40 % occurring on freehold rather than leasehold land (Fensham *et al.* 1998). This concentration of clearing can be attributed also to the requirement for landholders to obtain permits for clearing leasehold land.

**Chapter 1 Introduction** 

In 1995, tighter clearing controls were imposed on leasehold land and this led to clearing rates on freehold land increasing by 55 % after 1995. In contrast, clearing on leasehold land fell by 12 % (QLD DNRM 1999b). In December, 1999, the Queensland Government, under the leadership of Premier Peter Beattie, passed legislation to control clearing on freehold land with a view to giving the State greater power to regulate vegetation clearing on freehold land. The development of a State vegetation management policy, approved by the Governor in Council, was also required which included criteria for assessing development applications that involved clearing. Penalties for illegal clearing (up to AUD\$125,000) were imposed and courts were given power to order restoration of damage caused. Provisions for enforcement and compliance were also introduced.

Despite this advance, for the legislation to be proclaimed, a significant contribution in funding was required by the Beattie government to compensate farmers for not clearing their land. This led to an impasse (between December 1999 and September 2000) between the Queensland State Government and the Commonwealth over who was responsible for compensating farmers. Both governments were placed in the difficult position of ensuring that farmers but also Australia's national GHG emissions and increasing problems of salinity associated with clearing were addressed. However, during this time, more than 758,000 ha of native vegetation had been cleared, partly in "panic" by farmers that were anticipating controls (Roberts 2003).

In September 2000, the Queensland Vegetation Management Act was proclaimed which was aimed at regulating clearing of endangered regional ecosystems on freehold land. In addition, the Land Act was amended to prevent clearing of endangered or vulnerable ecosystems on leasehold land. Further changes were also introduced which served to protect those areas

where the remaining remnant vegetation cover was at 30 % or less, regardless of whether the land was freehold or leasehold. As a result, during the 2000-2001 period, the clearing rate reduced to 378,000 ha year<sup>-1</sup>, representing a decline of 50% (QLD DNRM 2003).

### 1.7 Implications of land clearing

The clearing of vegetation in Queensland has and continues to remain a contentious issue, particularly as considerable evidence is emerging that such activity is leading to dryland salinity, loss of species diversity (particularly birdlife) and GHG emissions.

# 1.7.1 Dryland salinity

By 2050, the NLWRA (2001b) predicted that salt would poison over 17 million hectares of Australian agricultural land and affect a further 2 million ha of inland waters. The environmental impacts of salt rising through the soil include the loss of large areas of land to wasteland, identified only by dead trees and lifeless creeks and rivers. Dryland salinity can also affect water quality for both agricultural use (i.e., irrigation) and human consumption. The indirect effects on farmland and water supplies include declining populations in regional towns and damage to infrastructure (e.g., roads, buildings, parks). However, the loss of productive agricultural land and associated reductions in yields and economic prosperity are of greater concern.

# 1.7.2 Loss and extinction of fauna and flora

Native wildlife, through starvation, exposure, stress and the increased risk of predation, is particularly affected by the destruction and degradation of native woodlands. The Australian Conservation Foundation (ACF 2001) currently estimates that bird species including parrots, honeyeaters and robins, have been reduced in number by approximately 5 million each year through land clearing.

In terms of flora, the clearance directly results in loss of species. However, the indirect impacts of clearance involve the removal of many species of perennial grasses due to the grazing of sheep and cattle. Furthermore, these grazing stock are hard-hooved animals. In areas where overstocking occurs and also in the vicinity of watering points and stockyards, the topsoil is exposed to erosion by the weather and the hard hooves of these introduced animals (Galloway 1974, Young 1996). Trampling by these animals often leads to compaction of the soil, resulting in an increase in runoff and the recolonisation of only fibrous and unpalatable species (i.e., five minute grass *Tripogon loliiformis*). The increase in runoff results in the loss of valuable nutrients. In areas where there is a dominance of sandy soils, the clearance of scrub directly results in wind erosion of the soil.

### 1.7.3 GHG emissions

Through clearing of vegetation biomass and associated disruption of soils, losses of GHGs can be substantial, as reflected in Australia's NGGI. Most woody vegetation in Australia supports an above ground biomass of less than 100 Mg ha<sup>-1</sup> (Graetz 1995) although levels are highly variable depending upon the type of vegetation, the stage of regeneration and the extent of degradation. In the NGGI, and as indicated earlier, Australia estimates CO<sub>2</sub> emissions from landuse change based on the total emissions from all carbon pools (i.e., below and above ground biomass, soil carbon and litter).

Although attention has focused particularly on the carbon losses associated with vegetation clearing, the role of woodlands regenerating on cleared areas and the inadvertent growth of woody weeds has recently been highlighted (Burrows *et al.* 1998). However, the carbon sink associated with regenerating woodlands has proved difficult to quantify as an estimate of the fraction of cleared land regrowing for the inventory period and also the previous 24 years is required (NGGI 1997).

The increase in the density of woody shrubs in areas occupied previously by open woodlands or grasslands, herein referred to a woody thickening, is commonplace in Queensland but has also been observed in other parts of Australia as well as in Africa and South America (Scholes and van der Merwe 1996). The extent of woody thickening is so extensive that Burrows et al. (1998) suggested that as much as 100 Mt CO<sub>2</sub> equivalents might be sequestered annually by the 60 million ha of Queensland's grazed woodlands. The causes of woody thickening include the displacement of indigenous land management practices by modern systems, replacement of native browsing animals with domesticated stock, the invasion of exotic shrubs, poor pasture establishment clearing and different regeneration strategies following after initial abandonment or neglect of previously cleared areas. Climate variability, stage in the disturbance/recovery cycle and variations in CO<sub>2</sub> fertilisation and N deposition are also believed to lead to thickening (Gifford and Howden 2001). Although attention has focused largely on the clearance of vegetation for agriculture, forestry activities also impact on the levels of GHG emissions. Within Queensland, both the government and private landholders control approximately 191,000 hectares of plantation forests, which is the third largest area in Australia allocated to plantation forestry after New South Wales and Victoria (ABS 2001). These plantation forests contain predominately softwood species (e.g., Pinus radiata) as well as hardwood species, dominated by the eucalypts.

### **1.8** Spatially quantifying biomass (carbon) stocks

Although satellite sensor (particularly Landsat) data have allowed a better estimate of the areas cleared or regenerating, estimates of the changes in carbon associated with vegetation clearance, thickening and also regenerating forests (including plantations) have still remained uncertain because of the difficulty in estimating the above and below ground biomass which is spatially variable. A number of approaches for better estimating the biomass (carbon) of

Australia's forests and woodlands have been implemented or proposed, as outlined below.

### 1.8.1 Traditional approaches

The simplest approach to biomass mapping has been to group classes within existing vegetation maps and associate each group with the most appropriate estimate of biomass, as determined from field surveys. The main limitation to this approach, however, is that existing vegetation maps are often lacking in consistency and inclusiveness of all vegetation types (Bergen *et al.* 1998). Within each class, vegetation is generally assumed to be homogeneous and often in a mature state whereas, in reality, a range of regeneration and degradation states may exist and the growth response of vegetation will also vary with different soil and climate regimes. A further limitation is that the quantity of available biomass estimates is far lower than the number of vegetation classes defined, and the estimates used are rarely representative of the class with which they are associated. Most biomass estimates are also biased towards commercial forests and are often derived from timber volume and wood density estimates with little consideration given to the below ground and non-commercial components such as the leaves and branches.

An alternative approach has been to model the distribution of potential vegetation types based on biogeographic information, including species ranges and climate and soils data, and again assign an appropriate biomass estimate. With this approach also, the same limitations outlined above apply. Advancement on this method has been to model and map potential biomass using spatial datasets on terrain-adjusted soils and climate and remotely sensed data as input to forest growth models (Landsberg and Waring 1997; 3PG AGO 2002c). Although demonstrating enormous potential, such approaches are generally restricted to even aged forests with closed canopies and have been difficult to validate due to the lack of appropriate ground data.

### 1.8.2 Use of optical remote sensing data

A number of land cover mapping projects (e.g., Barson *et al.* 1998, Kuhnell *et al.* 1998) have investigated the variation in and links between land use and woody vegetation. An approach that has been increasingly adopted in Australia has been to relate field estimates of surrogates for biomass to remotely sensed data from optical satellite sensors such as the Landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR) data. The acquisition of time-series of Landsat sensor data for land cover change assessment by both Federal and State agencies has certainly been an incentive for focusing on these datasets. However, a limitation to the use of data from optical sensors is that only the two-dimensional structure of vegetation can be determined, and the data is related only indirectly to biomass (Harrell *et al.* 1997).

### 1.8.3 The use of Synthetic Aperture Radar (SAR)

SAR is an active remote sensing system in that it generates it own energy source and is therefore independent of solar illumination. The signal or backscatter returned to the propagating antenna provides information on the texture and moisture content of surface material, which is different from, but complementary to, the compositional data acquired through optical systems. Parameter characteristics of a radar system include wavelength, incidence angle and polarisation, all of which can be optimized to acquire information about the type of surface materials or objects being sensed.

Unlike visible, near infrared and mid infrared wavelengths, microwaves from SAR have the unique capacity to penetrate layered materials to varying depths and provide information on the three-dimensional structure of vegetation. In particular, microwave energy at X band (~3.5 cm) and C band (~5.6 cm) is particularly sensitive to surface scatterers which, in the case of vegetation, include leaves, twigs and smaller branches of the canopy layer (Wang *et al.* 1994, 1995). Longer wavelength energy at L band (~24 cm) and P band (~65 cm)

have been shown to interact with the larger components of the canopy, the trunks and soil boundary layers (Wang *et al.* 1994, 1995).

Several studies have shown that, using single polarized data, the total biomass of vegetation may be estimated (Kuplich *et al.* 2000, Austin *et al.* 2002, Castel *et al.* 2002, Salas *et al.* 2002) although C-band, L-band and P-band band data have been shown to saturate at a broad range of biomasses (Table 4.2; Chapter 4). However, by employing multi-band polarimetric data, the range of biomass detected by SAR may be extended. In addition, several studies (e.g., Beaudoin *et al.* 1994, Harrell *et al.* 1997, Hoekman and Quinones 2000) have demonstrated that polarimetric data may be better used to estimate the component biomass of vegetation.

In Australia, the use of both spaceborne and airborne Synthetic Aperture Radar (SAR) for quantifying forest biomass has not been rigorously investigated. This is despite the availability, since 1991, of SAR data from a range of airborne and spaceborne sensors including the European Earth Resources Satellites (ERS-1 and ERS-2), the Canadian RADARSAT, the Japanese Earth Resources Satellite (JERS-1) Synthetic Aperture Radar (SAR), the Space Shuttle Imaging Radars (SIR-B and C) and the NASA JPL AIRSAR. This lack of research and development is surprising given the increasing demonstration internationally of the potential of SAR for biomass estimation.

Several reasons for this have been identified. First, the Australian Centre for Remote Sensing (ACRES) has, until recently, been unable to process the raw signal data acquired from spaceborne SAR. Second, SAR data has been treated with caution as there is evidence that the backscatter from vegetated surfaces is influenced by the water content of the vegetation as well as the roughness and orientation of the terrain. Third, the few studies (Witte *et al.* 1998) that have investigated the use of SAR data have had limited success, although this has
been due partly to the use of inappropriate surrogates of biomass (e.g., basal area) as ground data.

The use of SAR data for estimating the biomass of Australia's vegetation is however, advocated for several reasons. First, the majority of Australia's 155 million ha of forests are represented by woodlands, the biomass of which rarely exceeds 100 Mg ha<sup>-1</sup>. Therefore, the biomass of these woodlands should be quantifiable using, as a minimum, single polarised C and L band data. The Australian continent receives little rainfall compared to many regions of the world and the moisture content of vegetation is unlikely to vary substantially. Much of the landscape is also relatively flat and terrain effects are therefore minimal.

## 1.9 The NASA PACRIM AIRSAR Missions to Australia

An opportunity to better understand the role of SAR for retrieving biomass was provided by the 2000 NASA PACRIM II AIRSAR Mission to Australia. The AIRSAR instrument was designed and constructed by NASA's Jet Propulsion Laboratory and was intended for use by the scientific community to evaluate the potential of polarimetric and subsequently interferometry and polarimetric interferometry for land-based studies.

In 1993, the first AIRSAR mission to Australia was organised with a follow up mission in 1996. During these missions, the potential of SAR was evaluated. Based on the success of these first two missions, the third campaign (PACRIM II) was planned for September, 1999. Delays associated with damage to the aircraft led to the mission being postponed until August/September, 2000. However, data were acquired over a large number of sites in Australia during this period.

# 1.10 Pilot studies previously undertaken in semi-arid Queensland

In 1997, a study was undertaken in the Injune region investigating if any relationship existed between JERS-1 backscatter and the biomass of the sampled woodlands. LHH JERS-1 data was used to estimate trunk biomass (via empirical methods), while the foliage biomass was estimated (through empirical relationships with the NDVI). A model was subsequently employed where both these estimates were added together to give the total above-ground biomass.

The Injune study prompted a similar investigation in 1998, undertaken at Talwood, Queensland. In this study, historical Space Shuttle Imaging Radar (SIR-C SAR; 1994), AIRSAR topographic SAR (TOPSAR; 1996) and Japanese Earth Resources Satellite (JERS-1 SAR; 1995) data were employed. This facilitated the establishment of empirical relationships between the wavelength-polarisation combinations and the sub-component biomass, calculated via allometric equations. These studies served as a springboard for the current study and are briefly outlined in Chapter 4.

# 1.11 Thesis aims and research overview

With knowledge of the potential of SAR for quantifying biomass, requests were made for AIRSAR data to be flown over an area near Injune, central Queensland with the following aims:

- To evaluate the potential of airborne polarimetric data for quantifying the biomass and structural diversity of semi-arid Queensland woodlands, employing both empirical and modelling methodologies.
  - To explore the benefits of integrating optical remote sensing data

To achieve the above aims, the following was undertaken. First, an extensive review of the literature relating to both the ecological and technical aspects of the research was required.

Structural and species diversity, as well as a quantitative estimation of biomass was initially addressed prior to the collection of field data within the selected study area near Injune. Selection of Secondary Sampling Units was made on the basis of these classifications, facilitating the subsequent collection of field data. Concurrent with the acquisition of field data, the remotely sensed data was acquired, which included SAR, Lidar and CASI.

A quantitative evaluation of the species composition, the distribution and allocation of biomass according to species and the relationships between the structural parameters of each species is then undertaken.

The methodology for the estimation of biomass involves a number of components. The allometric equations are derived through destructive harvest, on the basis of three independent variables; diameter, height and crown area. These allometric equations in addition to a number of generic equations are employed to estimate the biomass within each of the 34 Secondary Sampling Units. A relationship between the actual biomass and the Lidar derived biomass for the 34 Secondary Sampling Units the basis upon which the Lidar is employed for the estimation of biomass (using height as the independent variable) across the entire study site (4500 Secondary Sampling Units).

The Lidar derived above-ground biomass estimates facilitated the establishment of empirical relationships between the estimates and the SAR backscatter. Simple regression analysis is employed to investigate these relationships. The relationship between actual estimates of biomass (from the 34 Secondary Sampling Units) and SAR backscatter were also explored, using

simple regression. On the basis of the coefficient of determination for each of the polarisation/frequency combinations, the influence of incident angle and levels of saturation, the utility of a biomass map for the Injune study site was determined. Scatterplots were employed to demonstrate the relationship between the Foliage Projected Cover and the SAR backscatter. This investigation focussed on the utility of the synergy between SAR data and optical data for the mapping of biomass in the semi-arid Australia.

On the basis of the strength of the relationships between the biomass and SAR backscatter for the AIRSAR strips, the backscatter from the dominant species associations, evident in 9 of the 34 Secondary Sampling Units sampled, was simulated according to a backscatter model for vegetation (Durden *et al.* 1989). Parameterisation of this model is described fully, in terms of inputs relating to parameters such as dielectric constant of the vegetation, branching angle and the trunk and leaf orientation. Analysis of Variance was undertaken to investigate the difference between the actual and simulated backscatter values. The backscatter was also simulated at a range of incidence angles.

With consideration of previous studies, employing spaceborne SAR for the investigation of vegetation biomass and results obtained as a result of this research, the use and potential of current and future spaceborne SAR for regionally quantifying and mapping woodland biomass and structure is discussed at length.

The integration of the optical data (e.g., Landsat ETM+) served primarily to assist in the registration of the SAR imagery and subsequently to assist in the accuracy assessment of the Lidar and CASI registration). Furthermore, estimates of Foliage Projected Cover for the entire study site (4500 SSUs) were generated from the Landsat ETM+ data.

### 1.12 Outline of thesis

Chapter 1 has provided a background to the study by emphasising the changes in land use and cover that are contributing to Australia's overall GHG emissions. Reasons for the recent spate of vegetation clearance in Queensland and the impacts on the environment have been presented. Traditional methods for quantifying GHG emissions associated with LULUCF have been reviewed briefly and the potential for integrating Synthetic Aperture Radar (SAR) data highlighted. The aims of the thesis have been presented.

Chapter 2 reviews vegetation biomass and relationships with carbon. Methods for quantifying the biomass of individual trees and scaling these estimates to the plot or landscape are reported and compared. The variability in biomass accumulation and allocation (to leaves, branches, trunks and roots) within and between vegetation types and the influence of climate, soils and topography is evaluated.

Chapter 3 discusses the reasons why vegetation biomass and structure may be quantified using SAR data. The physical attributes of vegetation that contributes to or influence the SAR return and factors that adversely affect SAR data (e.g., topography) are considered. The role of data acquired by optical sensors for characterising vegetation structure and biomass is reviewed.

Chapter 4 considers SAR variables of importance (e.g., wavelength and polarisation) and provides an overview of polarimetric signatures from vegetation and other surfaces.

Chapter 5 provides an overview of the Injune study area, focusing on the climate, soils, topography and vegetation types. The land use history of the area is reviewed.

Chapter 6 provides an overview of the sampling scheme implemented for remote sensing data acquisition. The use of large scale (1:4000) aerial photography (LSP) for directing the associated field campaign is presented. The collection of field data and destructive harvesting of selected tree species for biomass estimation is described.

Chapter 7 describes the acquisition of remote sensing data by a range of sensors including AIRSAR, CASI, and Lidar. Where data are used, methods for preprocessing are described and analysis of the large scale photography is presented.

Chapter 8 investigates the application of the allometric equations and the subsequent estimation of biomass. The utility of sapwood cross-sectional area for the purposes of the estimation of foliage biomass is discussed.

Chapter 9 provides an overview of the species composition and structural diversity and biomass of the woodlands at Injune, as obtained from analysis of Large Scale Photography. Relationships established between structural components are also presented.

Chapter 10 establishes empirical relationships between estimates of above ground and component biomass (derived from the field and finer spatial resolution remote sensing data) and the SAR data at different wavelengths and polarisations. Relationships with Landsat sensor data and derived products (e.g., Foliage Projected Cover (FPC)) are presented. The importance of woodland structure in influencing the SAR response is highlighted. Methods for mapping woodland biomass from SAR data are presented.

Chapter 11 outlines how the field and destructively harvested data are integrated to parameterise models that simulate the SAR return from the

woodlands at Injune. Methods for quantifying the dielectric properties and the geometry, size and density of trunks, branches and leaves are outlined.

Chapter 12 provides an interpretation of the SAR response as simulated for different woodland types using the SAR backscatter model of Moghaddam *et al.* (1994). The contribution of the return from different components of the vegetation and the interaction between components and the ground surface is reviewed. The scattering mechanisms operating within the woodlands are outlined and the influence of incidence angle is explored.

Chapter 13 provides a discussion of the role of SAR for quantifying the biomass and structural diversity of woodlands in Queensland and the importance of integrating optical data. Advanced approaches (i.e., inversion modelling) to mapping biomass and structure are proposed. The use and potential benefits of past (e.g., JERS-1 SAR), current (e.g., ENVISAT ASAR) and future (e.g., the Advanced Land Observing System (ALOS) Phased Array L-band SAR (PALSAR) SAR systems for quantifying woodland biomass and structure is reviewed.

Chapter 14 provides a summary of the work and presents the main conclusions and recommendations.

# Chapter 2

# **Vegetation Biomass and Carbon**

## 2.1 Overview

This chapter provides an overview of the role of vegetation biomass in the terrestrial carbon cycle and reviews procedures for quantifying biomass stocks, including strategies for sampling forest stands and deriving and applying allometric equations. Approaches to scaling from the plot to the stand level and converting biomass to measures of carbon are also outlined. Factors that influence the variability in biomass and also structure, including climate, soil, topography and human disturbance and management are also reviewed.

- 2.2 Biomass and carbon
- 2.2.1 Vegetation biomass

Biomass is defined as the total amount of living organic matter in organisms (e.g., trees) and is expressed as oven-dry weight (e.g., Kilograms, (Kg)). In vegetation studies, biomass is also used to commonly express mass (e.g., in tons (t) or Mega grams (Mg)) per unit area (e.g., per hectare (ha<sup>-1</sup>)), although biomass density is often considered a more appropriate term (Brown 1997). Biomass accumulates as a result of the process of photosynthesis, whereby light energy is utilized to convert  $CO_2$  from the atmosphere to chemical compounds. Subsequent partitioning of these compounds to the leaves, branches, trunks and roots then occurs (Landsberg and Waring, 1997). Vegetation biomass is comprised of lignin and carbohydrates, which varies within and between species. The carbohydrate fraction includes polymers of sugar molecules as well as larger carbohydrates such as cellulose and hemi-cellulose. The lignin fraction

is embedded in the cellulose matrix in the walls of cells, and provides a role in the support of the plant (Campbell 1993).

#### 2.2.2 Net Primary Productivity

The rate at which vegetation synthesises new biomass is known as primary productivity. The total of this productivity is termed Gross Primary Productivity (GPP) and is often calculated over specific (e.g., annual) periods and for specific unit areas (e.g., ha). The process of cellular respiration in plants requires a proportion of this GPP, such that the Net Primary Productivity (NPP; i.e., the net annual production of biomass) is determined as:

$$NPP = GPP - R_s$$
 Equation 2.1

where  $R_s$  is the energy used in respiration.

NPP encompasses both above (NPPA) and below (NPPB) ground primary production (Landsberg and Gower 1997) and is expressed typically in units of g С  $m^2$ **vr**<sup>-1</sup>. NPP correlates with photosynthesis, transpiration, evapotranspiration, productivity and yield rates and provides a highly synthesized, quantitative element for managing resources. NPP is also significant in biospheric models, and is often employed to describe annual rates of production of organic matter for the various global ecosystems. The average NPP and typical ranges for several terrestrial and aquatic ecosystems are given in Table 2.1, which shows that tropical forests and wetland environments are generally the most productive.

Ecosystem	Average	Typical Range
Equatorial rainforests	2000	1000-5000
Freshwater swamps and	2000	800-4000
marshes		
Midlatitude forests	1300	600-2500
Midlatitude grasslands	500	150-1500
Agricultural lands	650	100-4000
Lakes and streams	500	100-1500
Extreme deserts	3	0-10
Oceans		
Estuaries (tidal)	2000	500-4000
Continental shelves	350	300-600
Open oceans	125	1-400

Table 2.1Net Primary Production (NPP) for Various Ecosystems in g Cm² yr-1<br/>(Source: Strahler and Strahler 1987)

For forests, NPP is estimated commonly using a combination of plot-based sampling and allometry (see below for definition). However, due to the variability in the annual production of organic matter for different forest types, a combination of these approaches is considered optimal. In many cases, allometric equations that predict biomass are applied to plot-based tree recordings of species and tree size (Bergen and Dobson 1999). Although such an approach is useful for understanding carbon allocation within terrestrial ecosystems, the accuracy of NPP assessment is often questionable, partly because of the scarcity of allometric equations for estimating the production of biomass within different components (e.g., foliage and fine roots) and the poor ability to quantify the simultaneous production and shedding of tissues.

## 2.2.3 Biomass to carbon conversion

The biomass of vegetation also relates directly to the carbon content and indirectly to other nutrient elements (e.g., nitrogen). Knowledge of vegetation biomass can therefore be used to quantify carbon released through clearance, burning or sequestered through regeneration. Total carbon mass (M) may be regarded as the product of the area (A) of a particular form of vegetation and the mass of the carbon (in both biomass and soil) per unit area ( $M_A$ ). The conversion of biomass to carbon involves a carbon factor (Equation 2.2), which estimates the proportion of dry biomass that is carbon. A carbon factor of 0.5 is commonly employed, such that

$$C_T = B_T \times CarbonFactor$$
 Equation 2.2

where  $C_T$  is the total carbon and  $B_T$  represents total biomass (AGO 2002d). The carbon factor does, however, vary with species.

#### 2.2.4 Carbon to CO<sub>2</sub> conversion

Loss of carbon occurs largely through decomposition and burning. Decomposition occurs when fungi and bacteria decompose the organic matter of dead trees as well as any waste generated from live trees (i.e., bark and leaves). The organic matter is broken down to inorganic forms, in which they can be re-assimilated by other organisms. When burning occurs, carbon is released directly to the atmosphere. To convert to carbon dioxide equivalent (CO<sup>2</sup>-e), the carbon content (e.g., of a stand) is multiplied by a factor of 3.67, which represents the atomic weight of carbon (AGO 2002d).

In terms of units of measurement, the total, above/below ground or component biomass (e.g., leaf, branch, trunk or root) is expressed typically in kg per tree. When allometric equations are applied to plot-based measurements, where the plot is of known area, biomass is often scaled to a hectare (ha) and expressed as Megagrams (Mg) or tonnes ha<sup>-1</sup>. One Gigagram (Gg) equals 1000 t or one kilotonne (kt), while one Megatonne (Mt), or one million t, is equal to 1000 Gg. In this thesis, the units of kg tree<sup>-1</sup> and Mg ha<sup>-1</sup> are used.

## 2.3 Quantifying vegetation biomass

The biomass of individual plants (particularly trees) is commonly calculated from allometric equations that either estimate stem volume or biomass directly.

### 2.3.1 Estimates based on stem volume

In forestry, where timber yields are often expressed in terms of volume (e.g., m<sup>3</sup> ha<sup>-1</sup>), equations that relate tree size to stem volume and incorporate a form factor, are typically established. Measurements of height (H) or diameter (D, over bark (DOB) or under bark (DUB) and often at 1.3 m or breast height above the ground) are generally used as the independent variables and bark thickness may be considered. Stem volume is then calculated for each tree using Equation 2.3

$$V_{s} = \frac{\pi \times \left(\frac{D}{200}\right)^{2} \times H}{F}$$
 Equation 2.3

where  $V_S$  is stem volume is in cubic metres (m<sup>3</sup>), D is the diameter at 1.3m (either over or under the bark, depending on the expansion factor to be used) and F is the form factor (AGO 2002d). The form factor gives a summary of the overall stem shape and a value of 3 is typically used unless other data are available. The stem volume of each stem can be converted to biomass by multiplying by the basic wood density (e.g., g cm<sup>3</sup>), which can generally be obtained from published tables. The mass for each stem is subsequently multiplied by an expansion factor (AGO 2002d) to obtain the values for the tree. These expansion factors and wood densities are available for many species in Australia (e.g., NCAS 2000).

# 2.3.2 Estimates based on allometric equations

A limitation with estimating biomass from volume is that no consideration is given to the branch or leaf biomass. In forestry activities, there is often no need to estimate the biomass of these components as they are not exploited commerically. However, for carbon studies, the biomass of all components needs to be estimated, particularly as many species (e.g., eucalyptus) allocate a significant proportion of biomass to the branches. Therefore, for carbon-related studies, allometric equations that relate tree size to the volume or biomass of their components (e.g., leaves, branches, trunks and roots) are preferred for estimating the biomass of woody vegetation (Bergen and Dobson 1999).

Most allometric equations are formed by sampling individuals of a species across a particular size (e.g., diameter) range to obtain initially a wet and subsequently a dry weight of components (e.g., leaves, branches, trunks). From these samples, a wet:dry ratio is obtained which can then be multiplied by the wet weight of the tree components to provide an estimate of the total dry weight of these components or of the tree as a whole. Relationships are then established between an independent variable indicative of tree size (e.g., diameter, height or crown dimensions) and the mass of the components or their sum. A number of approaches to sampling the biomass of trees have been developed including importance sampling, randomized branch sampling, the use of the pipe theory model, double regression sampling and ratio sampling.

# 2.3.3 Importance sampling

Importance sampling (IS) is a technique requiring diameter measurements at two points along the tree stem, usually at DBH 130cm and near the top of the tree, from which tree volume is calculated using a taper function. This result is corrected subsequently using the square of the ratio of the actual diameter to that estimated by the taper function at a third selected height up the stem. This third measurement selects the height at random from a uniform distribution of tree volume up the stem and is known to be an unbiased estimator (Gregoire et

al. 1986). In terms of predicting the woody biomass (trunk and branches greater than 1cm in diameter), IS with Randomised Branch Sampling (RBS; see below) is considered a useful combination (Good 2001). Furthermore, the integration of IS and also centroid sampling (using a beta distribution) into a more generalised form of IS (Leech 1996) has been shown to be a more efficient method of estimating tree volume.

## 2.3.4 Randomised Branch Sampling

Randomised Branch Sampling (RBS) is an efficient, precise and unbiased method of estimating, for example, branch or foliage biomass and is a variation on sampling with probability proportional to size (Avery and Burkhart 1994). Using this method, the selection of branches for harvesting is based on probability roughly proportional to the biomass of the leaves/small twigs on the branch. The amount of branch/leaf biomass on the entire tree is then estimated by dividing the sample weight of the terminal branch (including or excluding leaves or leaves only) by the unconditional selection probability of reaching the branch. The variance is estimated by selecting multiple paths through the tree (based on diameters at each branching node), with between 5 and 10 paths (and the same number of end branches) required to estimate the biomass of the tree.

## 2.3.5 Pipe Model Theory

The Pipe Model Theory (Shinozaki et al. 1964a and b, Waring et al. 1982) is based on the observed relationship between conducting tissues (sapwood) and the tissues that receive water and nutrients in the crown. The theory suggests that the amount of leaves on a tree should be most closely correlated with the sum of the cross-sectional areas of living pipes supporting them which in turn can be approximated by the cross sectional area of the trunk at the height, just below the lowest living branch (Shinozaki 1964b). The physiological basis of the relationship lies in observations that water transport in trees occurs almost exclusively in the sapwood (Kramer and Kozlowski 1979) and that species differ in the saturated permeability of their sapwood (Whitehead et al. 1984). Several studies (Niklas 1995, Chiba 1998, Perttunen et al. 1998, Morataya et al. 1999) have used this model to develop equations to predict foliage area and/or biomass from the cross-sectional area of the stem and branch sapwood. As with the above observations, experimental reductions in leaf area resulting in the reduction in sapwood area have been undertaken predominately on fir species (Margolis et al. 1988) and pines (Kendall Snell and Brown 1978, Waring et al. 1982). Furthermore, trees that have experienced less inter-tree competition tend to add more sapwood basal area with equal amounts of foliage biomass (Morataya et al. 1999).

#### 2.3.6 Double regression sampling

This technique uses individual branches as sampling units (Attiwell 1966, Harrington 1979) such that regression equations are generated between dry weight and the diameter of primary branches. These regressions are then used to estimate the dry weight of the crown by measuring the diameters of all the primary branches. The estimated dry weight of the crown is then regressed against trunk diameter, for example, to develop regressions for the dry weight of the whole tree.

#### 2.3.7 Ratio sampling

Ratio sampling generally involves selecting and felling a number of trees across the observed size (e.g., diameter) range (and often encompasses a range of growth stages of varying diameters and height) and obtaining the fresh weights of the components (i.e., leaves, branches, trunks and roots) and sometimes subcomponents (e.g., branches 1-4cm, branches 4-10cm) as well as smaller samples of each. These sub-samples, as in many cases above, are subsequently oven-dried and the dry weight obtained. Equations are then generated between the dry weight and the size of trees. Although a sound approach to generating estimates of biomass, ratio sampling (Burrows et al. 1998) is often considered an expensive procedure, in terms of time, cost and use of resources and, for this reason, the range of equations is often limited and tends to focus primarily on the above ground components.

## 2.4 Independent variables

Each of the procedures outlined above ultimately establishes a relationship between the biomass of the tree components and an independent variable which is typically a measure of tree size. A range of independent variables are often used in the formulation of allometric equations, including diameter at breast height (~ 130 cm, DBH), H and even crown area (CA), with many relationships being of functional significance. For example, the relationship between DBH and H is often strong and indicates the mechanical support function of the stem (McMahon and Kronauer 1976). Consequently, the development of equations for the estimation of component and total above ground biomass using H and/or DBH as the independent variable (Harrington 1979, Tsair and Chin 1988, Harrington and Fownes 1993, Burrows et al. 1998, Kumar et al. 1998, San Jose et al. 1998, Medhurst et al. 1999) has been widespread. The use of CA as an independent variable has been less frequent due to the difficulty of obtaining crown dimensions, particularly in dense forest stands with overlapping crowns. The presence of gaps also influences the H-DBH relationship of the stand. For trees growing in stands, the rate of growth in H relative to the rate of growth in DBH is greater than for trees growing in open conditions, and is as a function of light availability and the mechanical perturbance by wind (Niklas 1995). In terms of allometry, rapid vertical growth and suppression of horizontal branching results in high allometric exponents (King 1981, Givnish 1988).

The structural characteristics of individual trees are an important determinant in the selection of an independent variable for allometric analysis. For example, the use of H as the independent variable for small trees and shrubs with multiple stems (e.g., the Australian woodland species Eremophila mitchelli (Sandalwood Box) might be most appropriate for estimating biomass. However, for those individuals with expansive or weeping crowns (e.g., Geijera parviflora or Wilga) or a large branching habit, such relationships may lead to error in the estimation of biomass, and crown dimensions (e.g., CA) may be more appropriate.

#### 2.5 Stand-based estimates of biomass

Stand biomass can be calculated from stem volume measurements or by applying allometric equations to the sampled trees within a plot. The following sections briefly outline how these are achieved.

## 2.5.1 Using volume equations

The biomass of the stand can be calculated according to the average biomass of the stem (as calculated from stem volume) and the number of stems in the stand, as illustrated in Equation 2.4.

$$B_{ST} = B_S \times n_s$$
 Equation 2.4

where  $B_{ST}$  is the volume of the stand,  $B_S$  is the average volume of the stem and  $n_S$  represents the number of stems per hectare. Stand volume is then converted to biomass to give a result in tonnes.

The basal area (BA) has also been related to biomass and is calculated from measurements of D via Equation 2.5

$$BA = \frac{\pi \times \sum (Diameter)^2}{40000}$$
 Equation 2.5

where the plot basal area is in m<sup>2</sup>. BA can also be calculated from angle counts of trees using a wedge prism or string gauge (Equation 2.6).

$$BA = n \times BAF \times \frac{1}{\cos \theta}$$
 Equation 2.6

where the plot basal area is measured in m<sup>3</sup> ha<sup>-1</sup>, BAF is the Basal Area Factor of the angle count instrument, n is the number of trees and  $\cos\theta^{\circ}$  is the cosine of the slope angle in degrees. Above ground biomass is subsequently calculated by multiplying the stand basal area by a basal area to biomass relationship.

## 2.5.2 Using allometric equations

According to the way in which the stand was sampled, there exist two ways in which stand biomass can be calculated if allometrics are employed.

- For fixed area plots (e.g., 50 x 50 m), all trees are measured (i.e., diameter or height) and biomass is calculated for each according to the equation and then summed for how many trees were in the plot.
- ii) Variable area plots are those in which a basal sweep was undertaken. This can be achieved using a wedge prism. This instrument incorporates a fixed angle and can be used to determine basal area. Those trees encompassed by the sweep are measured and their biomass, calculated subsequently. Similar to the fixed area plots, the biomass is then summed for all trees for which measurements were taken.

A number of limitations to the use of allometric equations have been identified. For example, although allometric equations have been developed for a wide range of species, these are often only applicable to forest plots located in the same type of forest and contained within the same environmental envelope. Furthermore, the applicability of these allometrics varies depending upon location (e.g., topography, soils) and the season (e.g., winter summer) or year (drought or wet) due to the resulting variability in the biomass of different components (particularly the leaves). If such differences are apparent, the utility of these allometric equations is dependent on the extent to which this variation can be predicted using, for example, site attributes (Medhurst et al. 1999) The application of the equations will also depend upon morphological differences and the stage of succession. For example, Burrows et al. (1998) formulated allometric relationships for the species Eucalyptus melanophloia (Silver leaved Ironbark), which is common to woodlands in Queensland, in both the mature and regrowth stages of development. This ontogenic distinction is fundamental to the accuracy of the derived biomass estimates for this species. Furthermore, in many natural forests and woodlands, including those in Queensland, there is enormous complexity in the structure and allocation of biomass due largely to the lack of uniformity with respect to species, age and general dimensional architecture. Changes in vegetation structure due to man-induced activities (e.g., woody thickening) also occur. For these reasons, the development and application of allometric equations, however derived, is complex.

#### 2.6 Influences on biomass

A number of factors are known to influence the allocation and accumulation of biomass by tree species, including climate, topography and human disturbance. The following sections provide an overview of some of these influences.

#### 2.6.1 Climate

Climatic regimes indirectly influence the distribution and allocation of biomass in vegetation as plant processes (e.g., photosynthesis, transpiration) are directly impacted by variations in climate. As a result, differences in biomass allocation to different plant components are responsive to the climate. In general, higher levels of biomass (and greater allocation to the above ground components) occur in wetter regions, decreasing with aridity. The equatorial, tropical and sub-tropical zones, for example, receive very high amounts of precipitation and the vegetation consists largely of tropical rainforest, monsoon forest and subtropical broadleaf evergreen forest. These forest types contain the largest amount of biomass. In Mediterranean climates, such as those typical to large parts of Australia, sclerophyllous vegetation is commonplace and is characterised often by woodlands with a biomass of less than 100-150 Mg ha<sup>-1</sup>. Within Australia, for example, coastal regions are cool and receive more precipitation than the interior, and support patches of sub-tropical evergreen forests, exhibiting a higher biomass than the woodlands. In the dryer semi-arid and arid zones, the biomass is generally lower. Individual species can demonstrate the impact of climate on biomass. For example, Acacia species typically form medium to tall open forests at the wetter end of their range but decrease in height and density with aridity, forming only low woodlands in dryer regions.

#### 2.6.2 Topography and soils

Soil forming processes are strongly dominated by climate and also topography (Strahler and Strahler 1987) and the distribution, type and structure of vegetation is often linked to soil type. Geomorphic factors also play a significant role in determining how wet or dry a certain area may be. At the local level, the steepness of slopes results in an increase in the rate at which the precipitation drains from the ground surface. Consequently, runoff increases, infiltration decreases and the soil often become thinner, due to erosion. Where the land is gently undulating, rainfall is able to penetrate the soil. Such a scenario results in fertile valleys, where vegetation flourishes and biomass is high. In addition, the slope and aspect are instrumental in determining the amount of radiation and wind exposure that vegetation receives and as a result, can produce different vegetation communities according to their location on the slope.

#### 2.6.3 Human Disturbance and Clearance

Vegetation clearance is another mechanism for inducing alterations in the composition, structure and biomass of forests and woodlands, due to its impact on light conditions and the general structure of the stand. Through clearance of forests and woodlands, changes in light regimes are introduced and the resulting variability in crown and canopy architecture within and between

cover types then influences the conversion of solar energy into biomass (Ceulemans et al. 1996). The spatio-temporal heterogeneity in the light environment is related to the observed differentiation in architecture and allometry among co-existing species (Kohyama 1991).

A further direct consequence of vegetation clearance is the occurrence of regrowth. Conventional logging may severely alter forest and species composition as the removal of large trees reduces biomass and the forest is subsequently dominated by secondary forest species. When a relatively undisturbed seed bank and sprouting stumps remain following clear-cutting or logging practices, fast regrowth occurs (Steinbeck 1981, Schacht et al. 1992, Sims et al. 1999) from both suckers and seedlings. However, with increased disturbance and intensities of use prior to regeneration, the tendency for regrowth to occur from underground root systems or as suckers from damaged stumps increases.

Coppicing is a process whereby harvesting or decapitation of certain plant parts will result in reinvigoration and even acceleration of growth in some species. Coppicing tends to encourage numerous slender trunks to regenerate from the root stock, drastically altering the root to shoot relationship of the plant. The ability to coppice confers a degree of resilience to natural and anthropogenic disturbance. Productivity and growth of coppiced individuals is also more complex than single tree growth due to a number of factors specific to coppicing practice. Rapid canopy development in coppiced stands, compared with seedlings, can be attributed to the larger number of stems per hectare (generally several sprouts per stump) and a faster growth rate of the sprouts due to an already established root system and carbon stored in stem bases, stump and root (Ceulemans et al. 1996). The presence of lignotubers is a characteristic of many Eucalyptus species that have been associated with sprouting. Lignotubers are swellings formed in the axils of the cotyledons as well as the successive new nodes of the seedlings.

In woody species, irradiance positively influences both height and diameter growth, resulting in a near linear increase in productivity with increasing light interception (Jarvis and Leverenz 1983, King 1991, Niinemets 1998). Changes in irradiance levels will result in differences in plant size, with a subsequent modification in biomass distribution and growth. Horizontal growth expands the area over which light can be captured. Thus, extremely uncrowded, understorey conditions favour very broad, low canopies that maximise a plants net rate of energy capture in the absence of competitors (Givnish 1988). In terms of the decomposition rates, increasing light interception by the forest floor may result in a slower rate due to higher temperatures and drier litter conditions, such that faster decomposition rates may be attributed to the investment of less energy in chemical defences and structural carbohydrates (de Mesquita et al. 1998). This is characteristic of secondary species. Environmental gradients have also been shown to significantly influence decomposition rates. Vucetich et al. (2000) used Scots Pine (Pinus sylvestris) forests to demonstrate that decomposition rates decreased with increasing latitude and increased with temperature and precipitation.

Following clearance, the increased light interception and subsequent changes in temperature, litter conditions and decomposition rates appear to impact on the physical nature of the regrowth species. As a result, the regrowth of many species (e.g., Eucalypts) tends to be multi-stemmed for several years, gradually thinning until only three or four or even one trunk remains (Tait 2000 pers. comm.). Unpublished data of Burrows et al. (1998) taken from Queensland's open woodlands revealed that for the first 5 and 9 years following the clearance of the E. populnea, E. melanaphloia and E. crebra, the average number of stems per regrowth individual was double that recorded for a control site (Figures 2.1a and b). It could be suggested that the increased number of stems support a wider crown.

## 2.7 Vertical and Horizontal Structure of Forests

Over the past 20 years, a number of methods have been presented concerning the comparison and statistical analysis of the horizontal and vertical structure of forests. In terms of relevance for this study, the structure of the forest needs to be clearly defined in terms of foliage and woody biomass distribution, since it is these elements which can subsequently be quantified and related to the SAR backscatter (i.e., C-band interaction with the foliage).

These methods range from simplistic to extremely complex and in most studies have been used in combination with each other. They include comparison of DBH and tree height using frequency histograms (Kuuluvainen et al. 1996, Lucas et al. 2002), definition of crown shells modelled on crown ratio, radius and shape (Song et al. 1997), the Pielou Index (Frohlich and Quednau 1995, Song et al. 1997, Neumann and Starlinger 2001) and the Shannon Index (Song et al. 1997, Neumann and Starlinger 2001). There are also a number of other measures relating to the evenness of the forest stand, its complexity, aggregation and the neighbourhood pattern of the trees that are contained (Neumann and Starlinger 2001).



Figure 2.1 a) A control site showing single-stemmed individuals of the species *E. populnea*, *E. melanaphloia* and *E. crebra* and b) multiple stemmed individuals of the same species but showing multiple stems due to repeated clearance. Both woodlands are approximately 5-9 years old (Burrows *et al.* 1998).

b)

a)

#### 2.7.1 Importance of the tree crown

Competition between trees in a stand influences the stem, branch and needle mass of an individual tree (Makinen 1997). The size and form of the crown has an instrumental role, in terms of how competition will affect the particular tree. For example, growth efficiency per unit of occupied area increases as the vertical crown projection decreases (Assmann 1970), suggesting that the most efficient stand structure is composed of trees with compact crowns (Makinen 1997). This is supported by Oker-Blom and Kellomaki (1982) who observed that light conditions of an individual tree are determined mainly by its crown structure. The crown biomass is made up of the foliage and branch biomass. Since the crown is supported by the trunk, the relationships between stem diameter, tree height and crown dimensions are fundamental to the maintenance of the mechanical stability of the tree (McMahon and Kronauer 1976).

Investigation of tree crown structural characteristics in Queensland woodlands is particularly important for a number of reasons. First, the crown structure is important for characterising and establishing the growth stage of the individual. Second, variations in tree crown size suggest the occurrence of trees at different stages of regeneration and/or degradation and are indicative of the variation in species within a stand. Third, the size and distribution of tree crowns is fundamental in determining the Foliage Projected Cover (FPC, %) of woodlands. Fourth, the amount and distribution of leaves and branches within the crown is important in determining the distribution of moisture within the stand and hence the dielectric properties. All of these factors are anticipated to influence the SAR response from woodlands and need to be considered if the interaction of microwaves with the vegetation is to be fully understood.

## 2.8 Variation in the Allocation of Biomass

Within natural stands containing a mixture of species and trees at different stages of regeneration and degradation, a range of growth forms are likely to occur. Within each, biomass allocation to different components will vary. Allocation of biomass to different components will also depend upon factors such as climate, spacing and growth form.

Dobson et al. (1995) described three broad categories of tree form.

i) The excurrent growth form characterises trees with a large, nearly vertical main stem, which results in apical dominance. Most coniferous species (e.g., firs, pines and spruces) exhibit this growth form and the majority of biomass is increasingly stored within the trunk as the tree matures (Figure 2.2a).

ii) The decurrent growth form is characterised by a complex branching structure through burification of woody stems. Hardwood species with this form include many North American and Eurasian species (e.g., oaks, maples) but also Eucalpytus and Acacia species. The majority of biomass within trees beyond the early stages of regeneration is allocated, in varying proportions, between the trunk and the branches (Figure 2.2b).

iii) The columnar growth form is characterised by a main stem crowned by a 'topknot' of foliage. Palms typify this growth form. This type does not occur in most woodland in Australia.

Examples of excurrent and decurrent forms are also compared in Figure 2.2c. Regardless of growth form, the allocation of biomass to different components of trees also depends upon a number of additional factors, including climate, stand structure and growth stage, and is dependent upon the plant's requirements for growth and maintenance. For example, in arid environments, there is a greater tendency for biomass to be allocated to the below ground components. The influence of climate was illustrated in a study (DeLucia et al. 2000) of Pinus species in montane and more arid areas, which indicated that the leaf/sapwood area ratio ( $A_L/A_S$ ; m<sup>2</sup>cm<sup>-2</sup>), which expresses the relationship between water conducting and transpiring tissues and relates to the Pipe Model Theory (Shinozaki et al. 1964a and b), was lower within the latter environment. This resulted in a more open crown and greater support of biomass in the sapwood rather than the foliage, since the combined increase in sapwood mass and decrease in leaf mass results in desert trees expending more photosynthate supporting structural mass and having less total leaf area than their montane counterparts (DeLucia et al. 2000).

Bernado et al. (1998) demonstrated that the allocation of biomass to different components for three species of Eucalypt was influenced by the spatial distribution of trees and, in particular, changes in the space between the trees. For example, if the space between individuals was to increase via gap formation, diameter to height ratio of trees is expected to decrease as they attempts to escape the lateral shading imposed by neighbors.

Biomass allocation to components also varies by growth stage. As illustration, sequestered carbon by plantations in Australia is calculated via an expansion factor, which is the ratio of total biomass felled in a forest (including branches etc, which are left behind), to the biomass (wood) removed (NGGI 1997). In the first few years of growth, high ratios were indicative of the first few years of growth, although the ratio dropped progressively as stands matured and as an increasingly higher proportion of biomass was contained in the stem (Kirschbaum 2000).



Figure 2.2 Examples from Injune study site of a) the excurrent growth form (*C. glaucophylla*) and b) the decurrent growth form (*E. melanophloia*) and c) adjacent individuals of decurrent (centre) and excurrent form.

# 2.9 Summary

To comprehensively describe the conversion of biomass to carbon and the subsequent carbon to  $CO_2$ , the role of vegetation biomass in the global carbon cycle was explored. This chapter also reviewed the variety of methods by which vegetation biomass could be quantified, at both the tree and stand level, including the use of volume measurements, basal area and allometric equations. The difficulties associated with their use were also discussed.

The importance of considering the structure of vegetation when calculating biomass was highlighted. Specifically, the chapter described the different tree forms (e.g., decurrent and excurrent) and also considered the range of factors (e.g., climate, soil and topography, human disturbance and growth forms) that influence the allocation of biomass to different components. Most importantly, the chapter outlined and gave an insight into the factors that should be considered when attempting to understand the interaction of microwaves with different components of the vegetation. In Chapter 3, a background to SAR is given whilst in Chapter 4, the use of this technology for characterising vegetation is outlined in more detail.

# **Chapter 3**

# SAR Theory and its Application to Vegetation

# 3.1 Overview

SAR typically operates in the microwave region of the electromagnetic spectrum at a wavelength of between 2.4 and 100 cm. This chapter explores the basic principles behind the propagation of microwave radiation from SAR and the interaction of microwaves with vegetation. This necessitates an understanding of radar polarimetry and the information that may be extracted from the Stokes matrix (van Zyl et al. 1987). A number of other factors considered important in the interpretation of the SAR response, including incidence angle and frequency of the backscatter, are reviewed. However, further information can be found in key texts such as Ulaby et al. (1986).

# 3.2 SAR variables of importance

The interaction of microwaves with vegetation and other surfaces varies with wavelength (or frequency), polarisation, incidence angle and phase. The following sections provide an overview of these parameters and their importance for characterising vegetation.

In a forest scattering situation, the dynamic range of the SAR data is represented by variations due to frequency, polarisation and incidence angle and also to the type of forest and underlying soil (Le Toan et al. 1992).

#### 3.2.1 Wavelength or frequency

The wavelength  $(\lambda)$  describes the distance between crests of a sinusoidal wave. The frequency (v) of the wave is the number of crests to travel one wavelength per unit time. Frequency is converted to wavelength via the radar wavelength equation

$$c = \lambda v$$
 Equation 3.1

and

$$\lambda = \frac{3.10^8 \, m \, \text{sec}^{-1}}{v} \qquad \text{Equation 3.2}$$

where c is the speed of the electromagnetic radiation.

Microwaves of different frequency penetrate to different depth within a forest canopy. At C-band, and particularly in closed forests, penetration rarely exceeds the crown thickness. However, at longer wavelengths (i.e., L-band and P-band), microwaves penetrate the crown layer, although some interaction takes place, but can also reach the ground surface such that interaction between the ground and both trunks and branches occurs. C-band data was reported by Green (1998a) to have the lowest dynamic range. This was attributed to its inability to penetrate the forest canopy to the same depths of L- and P-band. As a result, C-band microwaves were not subject to the same degree of attenuation.

Microwaves of different frequency therefore provide differing levels of information on the forest canopy. In particular, high frequency microwave energy at X band (frequency 8.0-12.5 GHz, wavelength of 3.74-2.4 cm) and C band (frequency 8.0-4.0 GHz, wavelength of ~5.6 cm) is particularly sensitive to surface scatterers which, in the case of vegetation, include leaves, twigs and smaller branches of the canopy layer (Wang et al. 1994, 1995). Longer wavelength energy at L band (frequency 2.0-1.0 GHz, wavelength of ~24 cm) and P band (frequency 1.0-0.3 GHz, wavelength of ~65 cm) provide information on the larger components of the canopy, the trunks and soil boundary layers (e.g., Wang et al. 1994, 1995).

#### 3.2.2 Polarisation

Wave polarisation refers to the direction of the electric field of the electromagnetic wave transmitted or received by a radar antenna. Figure 3.1 demonstrate horizontal (H) and vertical (V) wave propagation within an x, y plane. Both the horizontally and vertically polarised antennas are configured to transmit and receive waves that are orientated according to the inherent dimensions of the antenna. For H polarisation, the electric field wave crest is aligned along the H axis, whereas for V polarisation, the wave crest is aligned along the V axis.



Figure 3.1 Illustration of a) horizontally and b) vertically polarized waves

Despite the scattering effects of terrain and volumes, the nature of the backscattered signal remains a function of the polarisation of the incident wave. To maximise the amount of information extracted from the SAR imagery, multiple polarisations are employed to image the terrain. Fully polarimetric SAR, provided by NASA JPL POLSAR is able to measure the full radar response by operating in HH, VV or HV polarisation modes (Table 3.1). The reciprocity property of radar scattering demonstrates that the responses for HV and VH are identical.

For vegetation, the incident radar wave may enter the canopy and be depolarised by the canopy components (i.e., leaves, smaller branches or the trunk), which reflect the beam in different directions, a process commonly referred to as volume scattering. Where individual leaves, tend to hang in a particular direction, the backscattered signal will have a polarity parallel to the orientation of the leaves (Forster 1998). The leaves of many Eucalyptus species are predominantly vertically orientated (in the zenith direction). However, a change in orientation of the leaves (in the azimuth direction), may result as a function of the sun's position. Consequently, a differential SAR response might be expected.

In general, vertically polarised waves are capable to penetrate those targets with greater vertical orientation (Figure 3.2a), while horizontally polarised waves tend to be backscattered from targets of vertical orientation (Figure 3.2b). However, vegetation canopies are predominately horizontally orientated (i.e., branches in coniferous species). Thus, the horizontally polarised waves are more effective for canopy penetration and the vertically polarised waves are largely backscattered.

Designation	Definition	Terminology	
HH	Transmitted and received signals are	Co-polarised	
	horizontally polarised		
VV	Transmitted and received signal are	Co-polarised	
	vertically polarised.		
HV	Transmitted signal is horizontally polarised	Cross-	
	and only the vertical component of the	polarised	
	return signal is measured.		
VH	Transmitted signal is vertically polarised and	Cross-	
	only the horizontal component of the return	polarised.	
	signal is measured.		

Table 3.1 Transmit and receive polarisations typical to SAR



a)



Figure 3.2 a) Vertically polarised wave penetrating a vertically orientated target, b) Horizontally polarised wave backscattered from a vertically orientated target

b)

#### 3.2.3 Incidence Angle

The incidence angle ( $\theta$ ) describes the angle between the radar illumination and the ground surface (Figure 3.3). This angle is dependent on the height of the radar and increases from the near range to the far range, thereby influencing the viewing geometry. The term local incidence angle refers to the local slope of the terrain at any location within the image. This angle determines the image brightness for each pixel. The look angle is the angle measured from a vertical plane upward to a specific part of the radar beam. When the terrain is flat (i.e., horizontal), look and incidence angles are equal. The incidence angle is calculated such that:

$$\theta_i = \cos^{-1} \left( \frac{h}{R_0 + i\Delta R_0} \right)$$
Equation 3.3

where h is the altitude of the aircraft,  $R_o$  is the near range in the images,  $\Delta R_o$  is the size of the (slant) range pixels in metres and i is the line number of the object in the image (strictly valid for a flat earth only). SAR sensors on spacecraft have considerably smaller incidence angles than those mounted on aircraft, due to the differences in altitude.

For vegetation studies, consideration of the incidence angle is critical for several reasons. First, acute (low) incidence angles are known to offer better penetration of vegetation (Sader 1987, Pope et al. 1994, Moghaddam and Saatchi 1995), while the backscatter tends to decrease as the incidence angle increases. The influence of incidence angle on the individual backscatter mechanisms has also been explored. An increase in trunk-ground scattering corresponding to an increase in incidence angle was reported by Dong and Richards (1995).



 $\begin{array}{ll} Figure 3.3 \\ swath width; \tau_p, \ pulse \ length; \theta, \ incidence \ angle \ (Source: \ Ulaby \ \textit{et al.} 1996) \end{array}$
However, at high incidence, trunk-ground backscatter saturates and subsequently decreases, due to the increase in foliage volume attenuation. These findings concur with those of Imhoff (1995a), who reported that at larger incidence angles, the scattering mechanisms involving the crown layer begin contributing more to the total backscatter for L- and P-band. With respect to the branch term, backscattering from the branches is almost independent of incidence angle due to uniform orientation of the small branches (Dong and Richards 1995).

This dependence of backscatter on incidence angle also increases with the density of inclusions (i.e., leaves and branches) within the vegetation canopy and their average dielectric constants. In airborne SAR (e.g., AIRSAR), incidence angle in the range direction can vary from  $10^{\circ}-60^{\circ}$  and represents a significant disadvantage for land cover mapping applications, particularly as homogeneous vegetation can produce different backscatter signatures if imaged at various angles. For this reason, incidence angle correction is important so that subsequent processing errors are not amplified.

Over the past few decades, several approaches to incidence angle correction have been developed including normalisation of the SAR data by the total power (Yueh et al. 1988), generation of calibrated images, whereby homogenous areas had equal backscattering signatures (Sader 1987), the use of calibration ratios of the mean and standard deviation for selected image lines (Ranson and Sun 1994) and the use of a combined regression and normalisation approach using the backscattering coefficient (Saatchi and Rignot 1997, Saatchi and Moghaddam 2000). An alternative approach has been to combine information extraction to a limited range of incidence angles over a range of, for example, 10° (Hussin et al. 1991, Dobson et al. 1992, Rignot et al. 1994, Israelsson et al. 1994). Most of the spaceborne SAR systems have operated at incidence angles that are appropriate for quantifying the biomass of vegetation. For example, the JERS-1 SAR, operating at L-band HH and a look angle of 35°, provided a powerful means of discriminating woody from leafy biomass and total above ground herbaceous biomass. The SIR-C SAR acquired data at an incidence angle of 55°, over flat and hilly terrain, which was considered to be optimal for retrieval of forest parameters (i.e., bole volume, age, height; Beaudoin et al. 1995, Castel et al. 2000).

## 3.2.4 Phase Difference

Phase difference is a circular parameter, which has a range from  $-180^{\circ}$  for an even number of bounces to  $0^{\circ}$  for an odd number (Figure 3.4). The accurate measurement of the length of time taken for the transmitted radar pulse to return to the sensor is fundamental to the SAR image formation.





For vegetation, the phase difference can be interpreted to indicate the dominant scattering mechanisms. For example, a phase difference of  $0^{\circ}$  represents a single or odd return (e.g., 1, 3 or 5 bounces), while a phase difference of  $180^{\circ}$  is indicative of a double bounce return. Phase images provide a spatial measure of the phase difference between the horizontal and vertical return polarisations. This is discussed further in Section 3.3.3.2.

## 3.2.5 Other SAR measures

There have been a number of additional parameters and indices, which have been used to provide additional information regarding the physical character of the vegetation, and its backscatter response. These include the canopy structure index, the volume scattering index, the biomass index and the interaction type index (Pope et al. 1994).

In theory, these vegetation indices should provide considerable information concerning the biomass and backscattering response from the vegetation. However, where there are areas of non-vegetation or low biomass (Pope et al. 1994) the variability in backscatter may result in misleading outcomes from these indices. Consequently, these indices were not applied to the Injune dataset.

## 3.3 Radar polarimetry

# 3.3.1 Scattering Matrix

The quantity of incident power interpreted by the target and backscattered in the direction of the radar is defined using the scattering matrix. Each individual resolution element (pixel) within the radar image has an associated scattering matrix (S), which may be converted subsequently to the backscattering coefficient ( $\sigma^{\circ}$ ), a unitless quantity defined as the average radar cross-section (m<sup>2</sup> m<sup>-2</sup>) per unit area of the individual scattering elements (Zebker et al. 1987).

A similar matrix has been described by van Zyl et al. (1987), termed the Stokes matrix. It is derived from a set of scattering matrices, facilitating the calculation of the average scattering properties of a particular region. The scattering coefficient ( $\sigma^{\circ}$ ) can subsequently be synthesized for any desired combination of transmit and receive antenna polarisations (van Zyl et al. 1987). As a result, the variation of the scattering coefficient with polarisation can be measured via polarisation signatures for each point in the image.

#### 3.3.2 Polarimetric signatures

Polarisation signatures are generated as a function of the angles of ellipticity and orientation, and are subsequently utilised for the analysis of change within the radar cross-section. The ellipticity (ratio of the minor to the major axis) of the ellipse is given by the parameter ( $\chi$ ), while the orientation (of the major axis) parameter ( $\gamma$ ) describes the direction of the major axis of the ellipse (Figure 3.5).





These transformations require co-polar and cross-polar complex calibration (Zebker et al. 1987, Freeman et al. 1992) of the phase between elements of one scattering matrix. These polarimetric signatures are represented by three-dimensional graphs (Figure 3.6). Two types of graphs are generated, one which represents the co-polarised response, while the second represent the cross-polarised response. However, cross-polarisation differs from co-polarisation, in that the transmitting and receiving antennas are set orthogonally.

#### 3.3.3 Polarimetric Analysis of Vegetated Surfaces

Within forested areas, a high degree of depolarisation occurs due to the interaction of microwaves with different elements of the vegetation. The significant variation of vegetation elements on a scale smaller, equal to or greater than the resolution element combined with a strong randomly polarised return component, results in a relatively large coefficient of variation (COV) from vegetated areas (van Zyl et al. 1987). Strong differences also exist between forested and non-forested areas at certain polarisations, with the backscatter from non-forested (or cleared) areas containing a greater polarised component than forested areas (Zebker et al. 1987). This may be explained by the nature of volume scattering, which will not occur if the vegetation has constant dielectric properties. Analysis of polarisation signatures of forested areas by Zebker et al. (1987) has exhibited the properties of double bounce geometry, suggesting that the dominant backscatter mechanism from trees is double bounce geometry involving both the ground and the trees.



Figure 3.6 Polarisation signatures of a forested area and clear-cut area at C-, Land P-band (Source: Zebker and van Zyl 1991).

Extraction of biophysical and geophysical parameters from SAR imagery requires the use of statistical models or scattering models. Statistical analysis of polarimetric data can be undertaken through either data description, in terms of backscatter, polarimetric phase difference or polarimetric correlation (Hoekman and Quinones 2000), or through description of the cross products of the elements of the scattering matrix.

Hoekman and Quinones (2000) used kappa statistics to compare the results of the different combinations of frequencies for classifying tropical forest (i.e., primary forest, secondary forest, recently deforested and pasture). In terms of polarimetry and speckle, the multilook, Guassian Probability Density Function (pdf) of polarimetric phase differences and the polarimetric correlations were investigated via Kolmogorov-Smirnov tests of best fit, on the agreement of the theoretical used and the experimental observations. Consequently, LHV and PHV were considered the optimum wave parameter selection for biomass estimation.

## 3.3.3.1 Degree of polarisation

A number of indices relating to the extrema of the degree of polarization and total intensity have been used to characterize the scattering mechanism, which result from interaction with the target (Evans et al. 1988).

Touzi et al. (1992) differentiated targets within polarimetric data through derivation of four indices based on maxima and minimum of the degree of polarization and the total scattered intensity of a partially polarized wave. The dynamic range of the degree of polarization ( $\Delta p = \rho_{max} - \rho_{min}$ ) was used to estimate the degree of polarization sensitivity to the variation in the transmitted polarization. This index provided information on the scattering nature of the landscape (i.e., whether it was homogeneous or otherwise). The index was applicable to the measurement of the complexity of scattering mechanisms resulting from the spatial heterogeneity of the target structure.

The polarization purity of the return signal is established via these values in defining the fractional polarization F (Zebker et al. 1987, Durden et al. 1989), such that:

$$F = \left(\frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}\right)$$
 Equation 3.4

where,  $P_{min}$  and  $P_{max}$  are the minimum and maximum powers over both the copolarisation and cross-polarisation signatures. Van Zyl et al. (1987) approached the problem of target heterogeneity by defining the coefficient of variations (V), which is the ratio of the minimum to the maximum received power (Equation 3.5).

$$V = \frac{P_{\min}}{P_{\max}}$$
 Equation 3.5

where F is related to V by

$$F = \frac{(1-V)}{(1+V)}$$
 Equation 3.6

The polarimetric discriminators described above are appropriate for application to the Injune SAR data due to the heterogeneous nature of the woodland environment.

#### 3.3.3.2 Polarisation Phase Difference

Polarisation Phase Difference (PPD) is defined as the phase difference between the backscattered HH and VV fields (Dong and Richards 1995). In addition to measuring the various polarisations of the backscatter ( $\sigma_{hh}^{\circ}$ ,  $\sigma_{vv}^{\circ}$ ,  $\sigma_{hv}^{\circ}$ ), the polarisation phase differences between the multi-polarised backscattered waves can also be measured. According to Ulaby et al. (1996), the co-polarised phase difference (HH, VV phase angle difference), defined as:

$$\phi_c = \phi_{hh} - \phi_{vv}$$
 Equation 3.7

has proved to be a more useful parameter in image classification (in general) compared to the cross-polarised phase difference which is defined as:

$$\phi_x = \phi_{hv} - \phi_{vv}$$
 Equation 3.8

Polarisation Phase Difference has been employed by a number of studies, particularly those involving modelling of the SAR backscattered response, to investigate its relationship with forest scattering (Durden et al. 1989, 1991, Wang et al. 1993a, 1993b, Dong and Richards 1995). However, PPD is particularly sensitive to incidence angle. This is due to competing effects associated with penetration of the forest canopy decreasing with incidence angle and the projected cross-sectional area of trunks increasing with incidence angle (Durden et al. 1991).

Table 3.2Polarisation Phase Difference and associated scattering mechanisms<br/>(Source: Adapted from Wang *et al.* 1993a)

Polarisation Phase Difference	Scattering Mechanism	
VV-HH 0°	Single scattering	
<b>VV-HH 360</b> °	Single scattering	
<b>VV-HH 180</b> °	Double-bounce scattering	

#### 3.3.3.3 Polarisation Ratios

The use of polarisation ratios has not been common in recent years, however, was quite prominent 10 years ago, particularly in studies that modelled the SAR response from vegetation (Durden et al. 1989, 1991, Wang et al. 1993, Dong and Richards 1995). In a number of these studies, the polarisation ratios were employed to identify the dominant scattering mechanisms and subsequently verify the model response. The Polarisation Index and Linear Depolarisation Ratio are two examples of these ratios.

The Polarisation index ( $\rho$ ; Equation 3.9; Durden et al. 1989, 1991, Wang et al. 1993, Dong and Richards 1995) is related to the shape and orientation of the scatterers.

$$\rho = \frac{AverageHH}{AverageVV}$$
 Equation 3.9

However, Durden et al. (1991) maintained that the separabilities for  $\rho$  are too small, which indicates that it is not appropriate for distinguishing stands with similar structure but different biomasses.

The Linear Depolarisation Ratio (LDR; Equation 3.10) was employed by Durden et al. 1989, 1991), who reported that high values indicate scattering from the canopy, while lower values indicate surface and ground/tree scattering.

$$LDR = \frac{AverageHV}{AverageVV}$$
 Equation 3.10

Similar to  $\rho$ , the LDR demonstrates minimal separability and thus, indicates that the LDR is not strongly related to biomass (Durden et al. 1991).

# 3.3.3.4 Pedestal height

The pedestal is due to spatial variations in the observed scattering properties (Zebker et al. 1987, van Zyl et al. 1987, Durden et al. 1989) and is derived from the polarisation signatures. The pedestal height varies according to the type of scatterer, with heavy forest exhibiting a larger pedestal than a clear-cut area (Durden et al. 1989, Zebker and van Zyl 1991). The larger value is representative of a return, which contains a significant un-polarised component. This difference is evident at all frequencies, as indicated in Figure 3.5.

# 3.4 Summary

Wavelength and incidence angle of the radar wave are important considerations in the analysis of backscatter from different surfaces. This is a particularly important consideration when estimating vegetation biomass.

The information acquired from the target in terms of backscatter is interpreted by means of a scattering matrix. Polarisation signatures are derived from these matrices and provide a quantitative representation of the scattering surface. Phase difference, pedestal height, polarisation ratios and degree of polarisation analysis can be employed to provide information on scattering mechanisms.

In view of the minimal separabilities for both  $\rho$  and LDR and the sensitivity of phase difference to incidence angle, these polarimetric indices were not considered a viable option for the Injune dataset.

# **Chapter 4**

# Remote Sensing of Vegetation Biomass and Structure

#### 4.1 Overview

Studies worldwide have demonstrated the potential of SAR data for quantifying the above ground biomass of vegetation, particularly forests (Wang et al. 1994, Ranson and Sun 1994a,b, Kasischke et al. 1997, Grover et al. 1999, Austin et al. 2002). However, most have considered a relatively narrow range of forest types (often plantations), with the majority focusing largely on coniferous forests in the northern hemisphere, particularly in North America and Eurasia (e.g., Sader 1987, Rauste et al. 1994, Wang et al. 1994, 1995, Harrell et al. 1997, Baker et al. 1994, and Green 1998b, Balzter et al. 2002, Stankiewicz 2002). For this reason, the use of SAR for biomass estimation is still limited beyond these scientific studies and operational use is rare. Similarly, the use of SAR for characterising the structure of forests and woodlands has been demonstrated only for specific vegetation types.

This chapter aims to understand and present the reasons why biomass and structure may be quantified by SAR data for a range of vegetation types. Specifically, an overview of the physical attributes of vegetation (i.e., moisture content, geometric orientation of vegetative elements) that facilitate their characterisation using SAR is provided. Additional factors (e.g., incidence angle, soil moisture and topography) that influence the SAR response are outlined. The chapter also examines the relationships established between SAR backscatter and both total and component biomass for a range of forest types and relationships with other biophysical properties of vegetation (e.g., stem volume, crown surface area) is also considered, although in most cases these properties have been regarded as surrogates for biomass.

More recently, the focus of SAR research has switched from the establishment of empirical relationships between backscatter and biomass and related attributes to the simulation of the SAR return from vegetation, primarily through modelling. Over the past 15 years, there have been a number of models formulated that can be applied to a variety of vegetation types. For this reason, SAR simulation models are reviewed, including that of Durden et al. (1989) as this is used in this study. Through this description, the main scattering mechanisms associated with microwave interaction are also described. Lastly, the methods by which SAR data can be classified are examined, with special emphasis placed on image segmentation procedures.

#### 4.2 Physical basis for biomass estimation using SAR

Vegetation canopies consist of discrete dielectric inclusions (i.e., leaves, twigs, branches and trunks) that are distributed in and contain greater moisture content than the host material (air), which is commonly referred to as the continuous medium. SAR wavelengths that are larger in size than the inclusions are propagated through these canopies and the dielectric properties, geometry (orientation), dimensions, density and function of these inclusions govern the subsequent absorption ( $\kappa_a$ ) and scattering ( $\kappa_s$ ) of the radiation. Wavelengths that are smaller in size are attenuated for the same reasons, such that the wavelength enters the canopy but cannot be backscattered to the sensor due to attenuation by the branch layer. Otherwise, these short wavelengths do not penetrate beyond the canopy and are directly backscattered from the small twigs and leaves at the top of the tree crown. As the biomass of vegetation is also a function of the density of inclusions of varying dimensions and moisture content, direct relationships with the SAR return can be established.

#### 4.2.1 Dielectric Properties of Vegetation

The dielectric constant is defined as the ratio of the permittivity of a substance to the permittivity of free space. The average relative dielectric constant ( $\epsilon$ ) is a measure of the electrical properties of surface materials and consists of both a real ( $\epsilon$ ') and an imaginary ( $\epsilon$ '') part such that

$$\varepsilon = \varepsilon' + j\varepsilon''$$
 Equation 4.1

where  $\varepsilon$ ' is also referred to as the permittivity and  $\varepsilon$ '' corresponds to the dielectric loss factor of the material (j). To define the imaginary part of the dielectric constant, the index of refraction (n) is introduced (Ulaby et al. 1996), since the high frequency part of the dielectric response is equal to the square of the index of refraction. The dielectric constant ( $\varepsilon$ ) is therefore related to n by:

$$n = \sqrt{\varepsilon}$$
 Equation 4.2

As with the dielectric constant, the index of refraction is also composed of a real (n') and an imaginary part (n"), where:

$$n = n' - jn''$$
 Equation 4.3

These two parts are related to  $\varepsilon$ ' and  $\varepsilon$ " by

$$n' = \operatorname{Re}\{\sqrt{\varepsilon}\}$$
Equation 4.4 $n'' = \left|\operatorname{Im}\{\sqrt{\varepsilon}\}\right|$ Equation 4.5

and the inverse relationships are

$$\varepsilon' = (n')^2 - (n'')^2$$
 Equation 4.6

 $\varepsilon'' = 2n'n''$  Equation 4.7

The relative dielectric constant of vegetation material ( $\varepsilon_v$ ) is governed by the volume fraction of water in the material (VMC) and the dielectric constant of water ( $\varepsilon_v$ ) which typically has a value of 81 (Ulaby et al. 1986). The imaginary part of the dielectric constant is equally dependent upon water content but also on the concentration of mobile ions within the vegetation tissues (Moghaddam and Saatchi 1999).

The dielectric constant of vegetation is related to the dielectric constants of the individual leaves, branches, trunks and bark that constitute the vegetation. The leaves are the main sites for plant photosynthesis and transpiration and the cells and vascular systems contain significantly higher moisture content than the surrounding air. Within the branches and trunks, the sapwood, heartwood and bark represent the tree layers of dielectric media. Most of the water is contained within the phloem and xylem of the sapwood, as these are the main conducting elements for the transport of water and nutrients (Zink et al. 1997), with the phloem being the most active physiological layer.

The dielectric constant and also the volume fractions, vertical/horizontal distributions and orientations of the vegetation elements relative to the direction of the incident electric field vector are important determinants of the magnitude and phase of the microwave energy scattered back to the SAR. For example, the polarity of the radar return signal from leaves aligned in a particular direction will be parallel to the orientation of the leaves due largely to their high dielectric constant (Forster 1998). If these variations did not occur and vegetation exhibited constant dielectric properties, then volume scattering would not occur.

The dielectric constant of leaves can be estimated from measurements of volumetric water content and water potential (El-Rayes and Ulaby 1987). The dielectric constant of the woody components can be measured by penetrating the trunk/branch with a flattened bit and then inserting dielectric probes to specific depth increments (e.g., 1 cm). Generally, the dielectric constant of the bark is low but increases with depth to a maximum associated with the xylem (Way et al. 1990). To obtain dielectric constant values appropriate for the interpretation of C- and L-band backscatter, for example, measurements need to be taken from immediately under the bark (cambium) and the centre of the branch or trunk (non-cambium) respectively.

#### 4.2.2 Tree Geometry

Depending upon the form and growth stage of trees, the size and orientation of non-woody and woody (i.e., branches and trunks) components will differ. Within mono-specific plantations of similar age, the size and vertical/horizontal distributions of these components may be similar across larger areas. However, within forests and woodlands of mixed species, forms and age classes, the size and distributions of these components will be more variable and difficult to characterise.

Leaf orientation, in particular, is highly variable and can be categorised according to planophile (Equation 4.8) or erectophile (Equation 4.9; Lucas et al. 2002).

$$g_l(\delta_l) = 3\cos^2 \delta_l$$
 Equation 4.8

where leaf normals mainly vertical ( $\delta_i = 0$ )

$$g_l(\delta_l) = \left(\frac{3}{2}\right) \sin^2 \delta_l$$
 Equation 4.9

where leaf normals mainly horizontal 
$$\left(\delta_{l}=\frac{\pi}{2}\right)$$

As an example, regenerating tropical forest species (e.g., tropical Cecropia or Musanga species) may have planophile leaves whilst Eucalyptus species have erectophile leaves. Some leaves may be orientated in a dominant direction and this distribution can be described through the use of probability density functions.

The magnitude of microwave interaction with branches will depend largely on their size and dimensions. At C-band, Ferrazoli and Guerriero (1995) suggested that only a small fraction of the branch woody matter (mainly branches with radius < 0.8 cm) contributed to the return signal, particularly in closed canopies. At L-band, backscatter was considered to be due largely to interaction with branches of 0.5-1.5 cm radius whilst at P-band interaction occurred mainly with branches of > 1 cm radius.

Branch orientation can also be described through the use of probability density functions. The influence of the branch orientation on the SAR return will, however, depend upon the dimensions of the branches in relation to the wavelength. For example, at P-band, the orientation of large branches (e.g., greater than 10 cm diameter) will be an important influence on the SAR return but smaller branches (e.g., less than 1 cm diameter) will have little or no influence.

#### 4.3 Physical nature of SAR scattering

The following sections provide an overview of scattering from both the ground surface and the vegetation and the influences on the various scattering mechanisms.

## 4.3.1 Scattering from the ground surface

In sparse/open canopies, the backscatter signal from the soil complicates the retrieval of vegetation biomass as surface roughness and soil moisture as well as the depth of the surface litter also influences the SAR return. This subsequently introduces variability in scattering from the forest/woodland floor. SAR backscatter from the surface is also dependent upon the scattering and attenuation properties of the overlying vegetation.

#### 4.3.1.1 Surface roughness

For surfaces which are particularly rough, the incident SAR wave (at any angle aside from normal) is backscattered in all directions. This contrasts with the specular response from a perfectly smooth surface (Figure 4.1). A proportion of the incident wave is also transmitted below the air-surface interface, as an exponential function of the attenuation coefficient ( $\alpha$ ) of the medium into which it is penetrating. Equation 4.10 (Ulaby et al. 1996) relates n and  $\varepsilon$  to  $\alpha$ , where n is the index of refraction of the material and  $\varepsilon$  is the dielectric constant.

$$\alpha = \frac{2\pi}{\lambda} n'' = \frac{2\pi}{\lambda} \left| \operatorname{Im} \left\{ \sqrt{\varepsilon} \right\} \right|$$
 Equation 4.10



Figure 4.1 The angular distribution of energy scattered by its surface depends on its roughness (Source: Ulaby *et al.* 1996)

The impact of surface roughness on SAR backscatter is dependent largely upon the angle of incidence and wavelength (Bindlish and Barros 2000). To determine whether surface roughness or soil moisture is responsible primarily for the backscatter, C-band with a corresponding low incidence angle (i.e., 15 °) can be used (Taconet et al. 1996). This low incidence angle minimises the effect of surface roughness, as well as minimising the effect of the absorption by the vegetation canopy on the signal coming from the soil. C-band HH data tends to be less sensitive to surface roughness and more sensitive to soil moisture changes compared to C-band VV or HV data (Schmullius and Furrer 1992, Pultz et al. 1997). Wang et al. (1998) reported that C-band HH and VV backscatter were sensitive to surface parameters only within low biomass forest and at low incidence angles. At L-band, both HH and VV backscatter were influenced by surface parameters.

When considering the backscatter from soil surfaces, the contribution from volume scattering from the soil surface or within the soil needs to be acknowledged. Depending upon a number of factors such as wavelength, surface roughness and dielectric constant, the incident SAR wave may be backscattered directly or penetrate the soil surface to varying degrees. Consequently, volume scattering may occur due to the SAR wave interacting with the dielectric inhomogeneities beneath the surface, such as rocks and plant matter. According to Fung (1994), a larger dielectric constant typically causes a decrease in volume backscattering as well as a greater difference between HH and VV polarisations, which is attributable to the Brewster angle. For parallel polarised waves, the Brewster angle is the angle, where no reflected wave exists (Reppert et al. 2000; Equation 4.11).

$$\tan \vartheta_1 = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}}$$
 Equation 4.11

#### 4.3.1.2 Soil moisture

The soil contains variable quantities of water depending upon the type of soil (e.g., clay, sand or loam), the vegetation it supports and also local weather or climate conditions (rainfall, temperature). As a result, the dielectric constant will be affected. Sandy soils are typically well drained and are less adept at retaining water than clay soils. As an example, the dielectric constant approximates to 3-6 for well-drained sandy soils and 2 for clay soils (Hubbard et al. 1997). With increases in the soil dielectric constant, the SAR backscatter typically increases (Colwell 1983, Moghaddam et al. 1994) and a number of studies have observed significant relationships between surface soil moisture and SAR backscatter (Taconet et al. 1996, Su et al. 1997, Pultz et al. 1997, Srivastava et al. 1998, Wagner et al. 1999, Paloscia et al. 1999). The impact of changing soil dielectric constant is demonstrated also by the increased SAR backscatter of soil and also vegetation following rainfall (Saatchi et al. 1997). Furthermore, there exists a substantial layer of plant litter in most mature forests. Increases in the amount of dry plant litter, correspond to an increase SAR backscatter as a result of increases in the underlying soil moisture (Moran et al. 2002).

The influence of soil moisture on the SAR response can be explained as follows. For a particular surface, the backscattering coefficient (dB) is related closely to the power reflection coefficient (R), which describes the reflected power level relative to the incident power of the SAR wavefront such that

$$R = |\rho|^2$$
 Equation 4.12

where  $\rho$  is known as the Fresnel reflection coefficient of the air-surface interface. For conditions involving normal incidence and a lossless medium (conductivity considered zero), the Fresnel coefficient is

$$\rho_{normal} = \frac{1 - \sqrt{\varepsilon_r}}{1 + \sqrt{\varepsilon_r}}$$
 Equation 4.13

where  $\varepsilon_r$  is the dielectric constant of the ground.

Based on this formula<sup>1</sup>, a surface with a dielectric constant of 1 will lead to no reflection and 100 % transmission. As the dielectric constant ( $\epsilon_r$ ; or relative permittivity) increases, the percentage of the incident power reflected will increase. For example, a dry sandy soil with a dielectric constant of 3 will lead to 7 % of the incident power being reflected ( $\rho = 0.267$  giving R = 0.07) with the remaining 93% being transmitted into the sand. A water surface, which has a dielectric constant of 81, will reflect 64 % of the incident power ( $\rho = 0.8$  giving R = 0.64). Similarly, the velocity (V) of the electromagnetic pulse will decrease such that:

$$V = \frac{1}{\sqrt{\mu\varepsilon}}$$
 Equation 4.14

where  $\mu\epsilon$  represents the respective magnetic ( $\mu$ ) and electric ( $\epsilon$ ) components of the dielectric constant, described in terms of:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$
 Equation 4.15

where  $\epsilon$  and  $\epsilon_0$  are the permittivities of the real surface and free space respectively and  $\epsilon_r$  is the relative permittivity (or dielectric constant). Free space is represented by a relative permittivity of 1.

<sup>&</sup>lt;sup>1</sup> The Fresnel reflection coefficient of light is a function of an angle of incidence and water refraction coefficient. The water refraction coefficient is a complex value with the imaginary part of the order of 1x10<sup>7</sup> to 1x10<sup>4</sup> (Haltrin 1998).

#### 4.3.2 Scattering from vegetated surfaces

If the vegetation is sufficiently tall (generally > 15cm) or dense, it will influence the backscatter from the soil surface. In comparison to backscatter from the bare soil, a vegetation dielectric constant exists and needs to be considered. The radar backscatter for a surface, covered with vegetation consists of three types of contributions (Ulaby et al. 1996) as outlined in the Equation 4.16.

$$\sigma^{\circ} = T^2 \sigma_s^{\circ} + \sigma_{dv}^{\circ} + \sigma_{int}^{\circ}$$
 Equation 4.16

These are the backscatter contribution of the (bare) soil surface ( $\sigma_s^{\circ}$ ), the direct backscatter contribution of the vegetation layer ( $\sigma_{dv}^{\circ}$ ) and multiple scattering involving the vegetation elements and the ground surface ( $\sigma_{int}^{\circ}$ ). The two-way attenuation of the vegetation layer is described by ( $T^2$ ). These interactions are briefly outlined below and a fuller overview of the vegetation scattering is provided in Section 4.5.

The backscatter contribution of a bare soil surface is typically single bounce or surface scattering which occurs where the incident wave is returned directly to the receiver without interference from other scatterers. The two way attenuation from the vegetation layer involves volume scattering of the incident wave, particularly at higher frequencies and is attributable to depolarisation of the wave by multiple scatterers of varying size, orientation and dielectric characteristics. Through this process, a proportion of the scattered energy is directed towards the receiver. Multiple scattering terms are those involving the double bounce interaction, where the incident wave strikes two surfaces in a specular manner, such that the wave ultimately travels in the same direction as the incoming wave. Double bounce scattering is particularly dominant where vertically-orientated structures (e.g., buildings, tree trunks) occur on a horizontal surface. As an example, double bounce is particularly noticeable in flooded forests (Rosenqvist et al. 1999). However, double bounce scattering can occur from the branch layer as a function of the size, orientation and dielectric characteristics of the scatterers.

# 4.4 Considerations in the analysis of SAR data

In terms of pre-processing and analysis of the SAR data, consideration should be given to the influence of physical factors, such as soil moisture and topography. Quantitative measurements of the soil water content can be acquired, while topographic effects can be resolved as part of pre-processing procedures. These are discussed below.

# 4.4.1 Soil moisture

Soil moisture content is typically expressed in gravimetric or volumetric units. For the purpose of SAR investigation, volumetric measurements of soil moisture are preferred as the dielectric constant of the soil-water mixture is a function of the water volume fraction in the mixture (Hallikainen et al. 1985). According to Ulaby et al. (1996), the frequency range commonly considered for soil moisture sensing is that of 0.4-10 gHz, which encompasses C-, L- and Pband data.

Given the volumetric moisture content of the soil and composition in terms of clay and sand, the soil dielectric constant can be obtained via the polynomial derived by Hallikainen et al. (1985).

$$\varepsilon = (a_0 + a_1S + a_2C) + (b_0 + b_1S + b_2C)m_v + (c_0 + c_1S + c_2C)VMC^2$$
 Equation 4.17

where S and C represent the sand and clay textural components of the soil respectively (in percent by weight),  $a_0$ ,  $a_1$ ,  $a_2$ - $c_0$ ,  $c_1$ ,  $c_2$  are constants for  $\varepsilon$ ' and  $\varepsilon$ '' at each frequency and VMC is the volumetric moisture content. Alternatively, a number of researchers have adopted semi-empirical approaches (Dubois et al. 1995, Oh et al. 1992), which relate the backscattering coefficient to the soil

volumetric moisture content. This approach involves the solving of simultaneous equations and application is site and condition specific. The conversion of soil dielectric values into average volumetric soil moisture content by Pultz et al. (1997) was undertaken using the relationship established by Topp et al. (1980).

4.4.1.1 Measurements involved in the determination of soil moisture

As SAR wavelengths penetrate different layers of a medium and provide subsurface information, soil moisture measurements need to be acquired from more than one depth. The horizontal and vertical variation in soil water content (Ladekarl 1998) can be measured using Time Domain Reflectometry (TDR), gravimetric measurements, volumetric measurements (Srivastava et al. 1998) or a combination of TDR and gravimetric methods (Benallegue et al. 1995, Pultz et al. 1997, Meade et al. 1999). Where these methods are combined, comparisons can be made and equations formulated for the derivation of volumetric water content (Meade et al. 1999). Volumetric measurements involve the simultaneous measurement of bulk density. However, gravimetric soil moisture measurements can be converted to volumetric soil moisture, using bulk density measurements. Equation 4.18 represents the method by which the gravimetric water content is obtained, while Equation 4.19 demonstrates the conversion of gravimetric water content to volumetric water content.

$$GWC = \left(\frac{Soil \cdot wet \cdot weight - Soil \cdot dry \cdot weight}{Soil \cdot dry \cdot weight}\right)$$
 Equation 4.18

$$VWC = GWCx \frac{BD \cdot of \cdot soil}{Density \cdot of \cdot Water}$$
 Equation 4.19

The gravimetric method of obtaining moisture content, as described by (Klute 1986) involves weighing the wet soil sample followed by oven-drying the

sample to remove the water and then re-weighing the sample to determine the amount of water removed. Water content is then obtained by dividing the difference between wet and dry masses by the mass of the dry sample to obtain the ratio of the mass of water to the mass of dry soil. When multiplied by 100, this becomes the % of water in the sample on a dry weight basis. The volumetric water content is then calculated by multiplying the Gravimetric Water Content by the bulk density of the soil divided by the density of water (Equation 4.19).

Time Domain Reflectivity (TDR) is a method by which volumetric soil water content and dielectric constant measurements can be acquired directly (Borner et al. 1996). The TDR, a dual probe sensor of length (L) is embedded in a soil and uses the apparent dielectric constant ( $k_a$ ) of the surrounding soil to calculate the water content. The transit time (t,) of a voltage pulse applied to the sensor is used to derive the dielectric constant such that:

$$\varepsilon = \left(\frac{\frac{ct}{2L}}{2}\right)$$

Equation 4.20

where c is the velocity of light in vacuum.

An advantage of this method is that direct measurements of volumetric water content and soil dielectric constant can be acquired simultaneously. Although TDR is commonly used, a limitation is that in dry, compacted soils that contain gravels or large stones, probes often cannot be inserted to the desired depth. Furthermore, moisture measurements need to be taken at more than one depth level and at several locations. Measurements to depths of several cm are particularly important as the longer wavelengths (e.g., P-band) can penetrate this distance, thereby providing information on the subsurface properties depending on sensor and surface properties.

#### 4.4.2 Topography

The accurate interpretation of radar backscatter may be significantly hindered as a result of the topography of the area being imaged. Associated topographic errors include relief displacement, foreshortening, terrain layover, and radar shadow.

Relief displacement occurs as a result of the illumination of a scene from an oblique perspective. As a result, areas elevated above a datum level are displaced toward the radar resulting in higher objects appearing as if they are closer to the radar.

Foreshortening occurs where the observed position of the terrain slopes facing toward the radar antenna will be displaced toward nadir (i.e., foreslopes are shortened relative to their true length). Consequently, the compression of those features appears relatively brighter in the radar image. Foreshortening is maximised when the local incidence angle is 0° such that the base, slope and top of the elevated surface are imaged simultaneously and thus occupy the same position in the image. Foreshortening effects for a given slope may be overcome to a degree, by increasing the incidence angle. For example, where the average incidence angle approaches 90°, foreshortening effects are eliminated but severe shadowing may occur. Digital Elevation Models (DEMs) may be used during geometric correction to compensate for the across track compression of the radiometric information backscattered from fore slope areas (Ranson et al. 2001).

Terrain layover is an extreme form of foreshortening and occurs when largescale terrain slopes become normal or greater than the direction of propagation (where the radar angle of depression  $\theta^{\circ}$  is less than the terrain slope  $\lambda$ ). As a result, the ordering of surface elements on the radar image is the reverse of the ordering on the ground (Avery and Berlin 1992). Such layover zones generally appear as bright features on the image due to the low incidence angle. Additionally, the layover zone contains radiometric information that is the result of the superimposition of the response of many objects. Consequently, geometric correction will not resolve displaced areas in the image.

Radar shadow areas are created when 90°-  $\theta$  is less than the terrain slope  $\lambda$ . Shadows in SAR images represent areas on the ground surface that are not illuminated by the radar. As there is no return signal to the sensor, radar shadows appear very dark with respect to tone in the imagery. As incidence angle increases from near to far-range, the illumination of terrain becomes more oblique and subsequently, radar shadows become more prominent in the farrange.

Terrain relief influences the SAR imagery by causing geometric distortions and creating strong radiometric effects (Stankiewicz 2002). However, when the area being imaged is of low relief, severe geometric distortions associated with topography are minimal. The estimation of biomass, involving SAR backscatter will certainly be influenced by the impact of the SAR interaction with the underlying terrain, particularly in regions where mountainous and hilly terrain dominates (Stankiewicz 2002). However, this interaction will be of minor significance if the terrain is flat or gently undulating.

A number of methods have been investigated recently to reduce terrain effects in SAR images, including radiometric correction using an illumination angle inferred from a DEM (Ranson et al. 2001) and standard correction procedures based on DEMs (e.g., those included within the Gamma Suite of SAR processing software) are available, particularly for spaceborne imagery. To reduce the topographic effect, band ratios may also be used since backscatter dependence on slope is similar for different frequencies and polarisations

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(Ulaby et al. 1986). An alternative model-based method for terrain effect correction (Sun et al. 2002) has been employed without the use of a DEM. However, this method is only appropriate where information on the land cover and multiple polarisation SAR data are available. Similarly, corrections have been undertaken for terrain slope-induced polarimetric effects in the azimuthal (along track) direction for geophysical applications (Schuler et al. 1999).

## 4.5 Relationship between SAR and vegetation biomass

The use of SAR for retrieving the above ground biomass of woody vegetation has progressed substantially over the past decade. Early research was limited to simple comparisons between backscatter intensity and ground based biomass measurements through regression analysis.

However, the deployment of multifrequency, multipolarimetric airborne radar has witnessed the emergence of considerable research involving backscatter modelling (Kasischke et al. 1994, Wang et al. 1998, Castel et al. 2001) and the detailed analysis of polarisation signatures (Durden et al. 1989, 1991, Saatchi and Moghaddam 2000). Table 4.1 outlines the SAR wavelengths and polarisations employed to investigate biomass retrieval, with most studies employing empirical relationships between biomass (or surrogates of biomass) and SAR backscatter at different wavelengths and polarisations.

Where direct measurements of biomass have been available, these have typically been used to estimate the total and/or component (leaf, branch and trunk) biomass of forest and woodland stands. Studies employing direct measurements include Lucas et al. (2000a), Saatchi and Moghaddam (2000) and Hoekman and Quinones (2000).

# 4.5.1 Empirical relationships

The employment of a multi-frequency SAR sensor facilitates a better interrogation of the interaction of microwaves of differing frequency and polarisation with the different vegetative components of the tree or stand. Since 2000, there have been very few studies which have investigated the relationship between vegetation biomass and SAR backscatter using polarimetric SAR data (Hoekman and Quinones 2000).

Forest Type	Author	Wavelength	Polarisation
Conifers	Sader 1987	L	HH, VV, HV
	Rauste et al. 1994	C, L, P	HH, VV, HV
	Wang et al. 1994	С	VV
	Wang et al. 1995	C, L, P	HH, VV, HV
	Harrell et al. 1997	C, L	HH, VV, HV
	Baker et al. 1994	C, L, P	HH, VV, HV
	Green 1998a	C, L	HH, VV, HV
	Castel et al. 2002	L	HH
Tropical	Luckman et al. 1997b	C, L	HH, VV, HV
	Foody et al. 1997	C, L	HH, VV, HV
	Salas et al. 2002	L	HH
	Kuplich et al. 2000	L	HH
	Takeuchi et al. 2000	L	HH
Boreal	Fransson and Israelsson 1999	L	VV, HH
	Green 1998b	C, L, P	HH, VV, HV
	Hyppa et al. 2000	L	HH
Eucalypts	Austin et al. 2002	L	HH

Table 4.1SAR research according to vegetation type and sensor specifications

However, there have been a number of studies that have employed JERS-1 data to explore the relationship (Salas et al. 2002, Castel et al. 2002, Kuplich et al. 2000, Takeuchi et al. 2000).

For most growth forms, it is generally acknowledged that microwaves at Xband and C-band interact largely with the leaf structures and twigs in the outer and upper layers of the crown and canopy (Israelsson et al. 1994, Wang et al. 1995a, 1995b). As a consequence of this limited canopy interaction, the backscatter at C-band is dependent largely on the branch layer parameters such as primary and secondary branch diameter length, dielectric constant, density and orientation angle (Moghaddam and Saatchi 1995). However, many investigators raise concerns regarding the ability of C-band SAR to accurately estimate biomass over a range of vegetation types and conditions, particularly as C-band backscatter from non-woody vegetation (e.g., grass) may be similar to that of closed canopies.

Longer wavelengths (i.e., L and P band) penetrate through the foliage such that interaction is largely with the woody components. The relative degree of interaction with different components (i.e., trunks and branches) has been difficult to establish, however, due partly to inherent relationships between trunk and branch biomass (Lucas et al. 2000a). Furthermore, in a mixed species forest, the distribution of biomass may vary according to growth form (i.e., excurrent and decurrent), which further complicates interpretation.

## 4.5.1.1 Excurrent growth form

For the excurrent growth form (i.e., conifers), L-band HH and P-band HH backscatter have proved most useful for estimating the above ground biomass (Wang et al. 1995), whereas P-band HV backscatter has been shown to provide the highest sensitivity with biomass for a number of other studies (Le Toan et al. 1992, Beaudoin et al. 1994, Fung 1994, Israelsson et al. 1994, Rauste et al. 1994). Both L-band HV and P-band HV demonstrated the highest variability over the range of excurrent forest types due to the volume scattering within the forest canopy and are less sensitive to incidence angle variation (Saatchi and Rignot 1997). In contrast, at C-band, Fung (1994) observed that incidence angle has a significant bearing on the importance of canopy components in dictating the polarization response.

In terms of sensitivity to the woody volume, the excurrent forest scheme is similar to the decurrent forest scheme, whereby HV data is the most sensitive yet almost insensitive to soil contributions. One significant difference exists between the forest schemes at both intermediate and high woody volumes. For the excurrent forms, the preferentially horizontal branch orientation results in the HH backscatter being greater than VV backscatter at L- and P-bands (Ferrazzoli and Guerriero 1995). The sensitivity and correlation of both L and P band backscatter with trunk biomass has been observed and explained by the greater penetration of microwaves at these frequencies (Beaudoin et al. 1994, Israelsson et al. 1994, Fransson and Israelsson 1999) and also greater double bounce scattering.

For the excurrent growth scheme, the sensitivity of L and P band backscatter to branch biomass (Beaudoin et al. 1994, Ferrazzoli and Guerriero 1995, Saatchi and Moghaddam 2000) is due largely to geometrical parameters (i.e., dimension and orientation). The corner reflector backscatter contributions of soil and soiltrunk are essentially co-polar and are useful indicators of tree volume sensitivity (Ferrazzoli and Guerriero 1995). When volume sensitivity is low, soil backscatter dominates. At intermediate values, the soil-trunk corner reflector is important, resulting in HH backscatter at a maximum, which is higher than VV backscatter. The best volume sensitivities, however, are obtained at HV polarisations, while HH and VV polarisations approach each other (i.e., become more similar).

## 4.5.1.2 Decurrent growth form

The decurrent growth form has a greater proportion of its biomass allocated to the branches and the range of branch orientations is greater. Within the decurrent growth form, both L and P-band data have been most useful for estimating biomass (Beaudoin et al. 1994). However, varying combinations of polarisations have been reported as optimal. For tropical regenerating forests, L-band HV backscatter was the best combination for vegetation discrimination (Luckman et al. 1997b) and also demonstrated the best possibilities for biomass estimation (Hoekman and Quinones 2000). The predominant allocation of biomass to the branches results in a greater VV and HV response at both L and P band compared to the excurrent growth forms (Imhoff 1995b, Luckman et al. 1997b). Within closed-canopies, comprised of trees with substantial crowns, branch volume scattering may provide the greatest backscatter for both HH and VV polarisations as single layer reflections from the trunk and soil surface are obscured (Freeman et al. 1992, Imhoff 1995a).

#### 4.5.1.3 Mixed forests with excurrent/decurrent forms

The majority of studies have focused primarily on forests that contain either excurrent or decurrent stands, with many focusing on plantation forests. However, where a mix of forms occurs, the SAR response is expected to be more complex and difficult to interpret. Such would be expected from natural forests, with a diversity of species and growth forms. As a result of the limited number of investigations into these mixed forests, a number of associated difficulties have become apparent. These include, considerable data dispersion occurs as a result of the variety of forest types, which is most pronounced at C-and L-band (Rignot et al. 1994). Also, the mixed forest biomass has been overestimated by 100% at circular polarisation, corresponding with a HH-VV phase difference which was twice the magnitude of unmixed forest of similar biomass (Rignot et al. 1995).

#### 4.5.1.4 Inherent Relationships between biomass components

In many situations, the specific interactions of microwaves with different woody components are difficult to establish. This is due partly to poor and often subjective mechanisms for determining the proportion of biomass contained within the branches and trunks, particularly as many allometric equations are not appropriate for calculating the allocation of biomass to different components (i.e., leaves, branches and trunks). Furthermore, it is evident that L band does not exclusively interact with the branches and P-band

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does not exclusively interact with the trunks (Lucas et al. 2000b) and that there is a certain degree of overlap between these elements, both in terms of their size and angular orientation, particularly in natural forests and woodlands.

Even so, there may be a distinction between L and P band return if the vertical distribution of woody elements within the canopy is considered. For example, Fung (1994) demonstrated that, for coniferous vegetation, the large branches dominate P-band volume scattering, while the volume-ground interaction is dominated by the trunk-ground component. However, Israellson et al. (1994), for species including poplar, indicated that P-band is more sensitive to changes in radius and length of canopy components, than to changes in stem density. In terms of polarisation, HH polarisation showed the greatest penetration and influence by terrain topography, soils and understorey vegetation (Beaudoin et al. 1994) and hence dominated ground-trunk scattering (Dobson et al. 1995). For similar types of tropical forests, Rignot et al. (1995) were able to distinguish biomass levels using P-band data, with P-band HV and HH data were most highly correlated with branch and stem biomass respectively.

#### 4.5.1.5 Use of Polarisation Ratios to investigate empirical relationships

The use of polarisation ratios has been suggested for quantifying biomass due to the stronger relationship observed in some studies (Foody et al. 1997) and their ability to differentiate canopy structures (Foody et al. 1997, Wu and Sader 1987). The correlation of image signatures is enhanced using polarisation ratios due largely to the different scattering behaviours of longer and shorter wavelengths (Ranson and Sun 1994a). Specifically, co-polarised ratios (e.g., LHH/LVV) have proved useful for identifying different canopy structures (Wu and Sader 1987) and also display sensitivity to trunk-ground interactions (Durden et al. 1991). Some ratios (e.g., PHV/CHV) have been found to show greatest sensitivity to above ground biomass (Ranson and Sun 1994a) although multi-frequency, cross-polarisation ratios (e.g., LHV/CHV; Dobson et al. 1995, Harrell et al. 1997) may not adequately account for the variations in canopy structure at a particular site. Proisy et al. (2000) used ratios to explore the dominant scattering mechanisms within mangroves whilst Green (1998b) established relationships between canopy closure and backscatter ratios.

Green (1998a) employed stem biomass, calculated from DBH and H and percentage canopy cover (estimated as the ratio of the number of closed canopy pixels to open canopy pixels) as the biophysical variables in the relationships with SAR backscatter from spruce forest. For stem biomass, significant relationships were observed with C-band HV and VV and L-band (all polarisations). For the percentage canopy cover, significant relationships were apparent for the ratios LHH: LVV, LHV: LHH, CHH: CVV, CHV: CVV, CHV: CHH.

In general, the main scattering mechanisms present vary according to the polarisation and wavelength of the incident SAR signal. C-band, being the shortest wavelength (~5.6cm), typically demonstrates only shallow penetration of the tree canopy. Much of the C-band backscatter originates from the leaves and small branches at the top of the canopy. However, C-band can be backscattered from elements deeper in the canopy or even from the floor of the forest. This occurs when there is opportunity for the wavelength to penetrate the canopy due to structural characteristics of the forest (i.e., forests of low density, with open canopies or containing numerous canopy gaps).

The longer L-band wavelengths (~ 24.6 cm) penetrate and interact with the larger branches in the canopy. This interaction can be classified into two forms. Firstly, the L-band signal can be volume scattered by the canopy constituents, whereby the incident signal is depolarised, resulting in cross-polarisation. Secondly, the incident signal can penetrate the canopy, be backscattered from the branch layer onto the ground surface and subsequently be backscattered from the ground to the sensor (i.e., branch-ground double bounce scattering). However, the most predominant form of scattering occurring at L-band is the

trunk-ground double bounce interaction. This is particularly prevalent in forests containing excurrent forms (i.e., coniferous species), whereby the largest proportion of biomass is allocated to the trunk component.

P-band is the longest wavelength (~ 68 cm) and can penetrate to the forest floor, even in relatively closed canopies. As a result, single bounce scattering can occur from the forest floor, whereby the incident signal or the backscattered signal, is not attenuated by the branch layer. Similar to the shorter wavelengths, there are contributions from the branch layer and the branch-ground doublebounce interaction. The strongest backscatter at P-band occurs as a result of the trunk-ground double bounce interaction. Surface effects are also an important consideration. The type of soil, in terms of sand and clay content, is instrumental in determining the water holding capacity of the soil and hence the scattering behaviour or microwaves.

#### 4.5.2 Saturation use of single and multi-band data

A recognised limitation of using SAR to retrieve biomass is that saturation of the C-, L- and P-band backscatter occurs above certain thresholds of biomass. The saturation threshold is determined typically through simple regression analysis (either through observation or mathematically) and is defined as being the point where the slope of the regression line between biomass and SAR backscatter (dependent variable) is at or near zero (Imhoff 1995b). This threshold is dependent upon wavelength, polarisation and SAR viewing geometry and tends to be larger for longer wavelengths with the HV and VV polarisations being the most and least sensitive respectively (Kasischke et al. 1997). In general, saturation of the C-, L- and P-band data occurs at approximately 20 Mg ha<sup>-1</sup>, 40 Mg ha<sup>-1</sup> and 100 Mg ha<sup>-1</sup> respectively (Imhoff 1995b). Although saturation of the relationship between SAR backscatter and biomass has been observed worldwide, there is still considerable variability between forest types, which can be attributed largely to differences in structure (Table 4.2).

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As the relationship between SAR backscatter and biomass saturates at relatively low levels of biomass, Imhoff (1995b) suggested that only approximately 4 % of the global terrestrial biomass may be quantified using, for example, C-band data alone and that SAR data were therefore best suited to estimating the biomass of agriculture and regenerating forests. Furthermore, confusion with other surface covers (e.g., non-forest) is common. This percentage of global terrestrial biomass able to be quantified is expected to increase if the longer SAR wavelengths were employed in global biomass mapping. These wavelengths demonstrate saturation at higher biomass levels (i.e., up to 200 Mg ha<sup>-1</sup>has been reported for P-band, thus are recommended for the mapping the biomass of vegetation supporting a high above-ground biomass, such as, dense tropical forests and the temperate forests of the mid to high latitudes.

#### 4.5.3 Other factors affecting estimation of biomass from SAR

A number of additional factors are known to influence the SAR return including rainfall. As a result of the sensitivity of the SAR signal to the moisture content (i.e., dielectric properties) of vegetation and soil, a rainfall event prior to or during the acquisition of SAR data can influence the radar backscatter. In addition to rainfall events, water can also increase within the soil as a result of factors such as a change in the elevation in ground water. However, the type and density of the vegetation are contributing factors in determining the extent to which the backscatter is altered. For example, greater backscatter was observed from tropical bamboo and regenerating forests in wetter periods, compared with mature forests using JERS-1 SAR L-band (Kuplich et al. 2000). When the longer SAR wavelengths are used, the backscatter is a result of the large biomass components, such as the trunk and the branches. Thus, the droplets of water on the leaves would result in insignificant backscatter. However, the presence of water droplets on leaves would increase volume scattering from the canopy at the C-band wavelength (Saatchi et al. 1997). 4.6 Relationship between SAR and biophysical properties of vegetation There have been numerous studies, which have employed various biophysical parameters in relationships with SAR backscatter. In many studies, allometric equations used for the estimation of biomass have not been available and have not been generated, since the derivation of species-specific equations is an expensive and lengthy procedure. In some cases, allometric equations are available for a particular species. However, many of these equations have been derived at a different site and at a different time of the year from where they are to be applied. This may be a source of inaccuracies in biomass estimation, due to the existence of environmental gradients and seasonal variability. As direct estimates of biomass are lacking for many forests, many studies have relied upon surrogates for biomass including vegetation height and crown depth (Martinez et al. 2000) or other tree/stand parameters (e.g., basal area, stem volume; Paloscia et al. 1999, Martinez et al. 2000).

		Threshold (Mg ha <sup>-1</sup> )	v ceranon 1) pc	
C-band	HH	60.74	Broadleaved woodland	Imhoff (1995a)
		60	Pine, Spruce, Fir	Rauste et al. (1994)
		147.90	Pine and broadleaf	Imhoff (1995b)
	VV	64	Pine, spruce birch	Fransson and Israelsson (1999)
	VV	57.35	<b>Broadleaved woodland</b>	Imhoff (1995a)
	VV	50-150	Pine forest	Wang et al.(1994)
		154.88	Pine and broadleaf	Imhoff (1995b)
	HV	140.29	<b>Broadleaved woodland</b>	Imhoff (1995a)
		153.62	Pine and broadleaf	Imhoff (1995b)
L-band	HH	143	Pine, Spruce, Birch	Fransson and Israelsson (1999)
		150	Pine, Spruce, Fir	Rauste et al. (1994)
		127.51	Broadleaved woodland	Imhoff (1995a)
		163.04	Pine and broadleaf	Imhoff (1995b)
		100	Eucalypt mixed woodland	Lucas et al. (1999)
		610	Eucalyptus forest	Austin et al. (2002)
		60	<b>Tropical rainforest</b>	Luckman et al. (1997b)
	M	79.04	<b>Broadleaved woodland</b>	Imhoff (1995a)
		190.31	Pine and broadleaf	Imhoff (1995b)
	HV	140.59	<b>Broadleaved woodland</b>	Imhoff (1995a)
		52	Tropical rainforest	Hoekman and Quinones (2000)
		155.65	Pine and broadleaf	Imhoff (1995b)
		60	Tropical rainforest	Luckman et al. (1997b)
P-band	HH	83.46	Broadleaved woodland	Imhoff (1995a)
		176.59	Pine and broadleaf	Imhoff (1995b)
	M	108.22	<b>Broadleaved woodland</b>	Imhoff (1995a)
		125.78	Pine and broadleaf	Imhoff (1995b)
	HV	114.89	<b>Broadleaved woodland</b>	Imhoff (1995a)
		560	Tropical rainforest	Hoekman and Quinones (2000)
		163.38	Pine and broadleaf	Imhoff (1995b)

#### 4.6.1 Stem volume

Stem volume was used by Fransson and Israelsson (1999) who observed that Cband was sensitive to low stem volume (equivalent to a biomass of 0-70Mg ha<sup>-1</sup>), while L-band was sensitive to stem volume in the range equivalent to a biomass of 0-160 Mg ha<sup>-1</sup>.

#### 4.6.2 Surface are and volume of the tree crown

Surface area and volume are geometric quantities that have also been employed to estimate the biomass of the tree crown, tree bole or both. Imhoff (1995a) employed three structural descriptors involving surface area and volume (Figure 4.2) for the description of stands of equal biomass, which were correlated subsequently with SAR backscatter.

Other studies (e.g., Green 1998a) have focused on gap analysis and tree crown analysis which involves the calculation of crown surface area and volume and other structural indices. Such calculations tend to be relatively straightforward to implement when monospecific stands of coniferous species are considered as these closely resemble the geometric conoid shape. However, in mixed species forests with a predominance of decurrent growth forms, other surface area and volume (e.g., paraboloids, hemispheres) calculations are required.

#### 4.6.3 Age of vegetation

A number of studies (e.g., Baker et al. 1994) have indicated that the age of forests may be estimated using SAR data, particularly when even-aged plantations or regenerating forests are encountered.



Figure 4.2 Demonstration of structural variation in forests having the same aboveground biomass (50 Mg ha<sup>-1</sup>), as modelled using MIMICS. The stand to the left has a low SA/V compared with the stand to the right (Imhoff 1995a).

However, these relationships rely primarily on a relatively consistent level of biomass accumulation with age between and within stands. According to Le Toan et al. (1992), the dynamic range of forest backscatter can be defined as the backscatter ratio between older forests and clear-cuts, which decreases with increasing frequency and decreases from HV to HH and then to VV. However, the penetration of the signal decreases with increase in frequency and hence the sensitivity to age also decreases. In such studies, Karam et al. (1995) and Fung (1994) indicated that the cross-polarised signal exhibited a greater dynamic range and hence sensitivity to biomass compared to like polarisations. This was particularly evident of P-band data, when coniferous forests were considered. In this study, the P-band HV backscatter was attributed almost solely to interaction with long branches of all ages. However, as the trees/stands aged, the P-band backscatter dominated by trunk ground interaction at HH polarisation changed to that directly from the branches at VV polarisation. For C-band and L-band, the dominant contributors to both like and cross polarisation radiation were the needles and branch twigs respectively, the biomass of which varied similarly with age.

#### 4.6.4 Canopy closure

Unlike optical sensors, which tend to observe the two-dimensional structure of vegetation canopies and are more sensitive to elements such as chemical composition (Jacquemoud et al. 1994, Goetz et al. 1997), canopy gap fraction (Green 1998a,b) and productivity, data from SAR can be used to interrogate the three-dimensional structure. In particular, the branches and leaves of canopies lead to depolarisation of the SAR signal and the differing orientation of these elements are often responsible for the characteristic polarimetric signatures associated with different forest types. Gaps between trees may also contribute to an increase in backscatter, particularly if the reflectance of the ground surface is strong by increasing trunk-ground double bounce scattering. These gaps may represent the forest response to disturbance or the means by which regeneration and succession is occurring. In Australian woodlands, tree gaps are an inherent characteristic of the vegetation structure. Tree gaps influence the relative intensity of backscattering components and the relationship between pixel size, size and spacing of individual trees and size and distribution of gaps determines the spatial characteristics (texture) of the image (Ranson and Sun 1997b).

The open nature of their canopies and the subsequent presence of gaps is a distinct characteristic of Australian woodland communities and are of particular importance when considering interaction of microwaves with canopy components and the ground surface. The existence of a closed vegetation canopy with dielectric inhomogeneities (i.e., leaves as the uppermost vegetation layer) attenuates C-band wavelengths such that little of the incident energy penetrates to the lower levels of the forest. In open canopies, however, the shorter C-band wavelengths are able to penetrate resulting in the return signal exhibiting a greater dynamic range compared to other frequencies (Green

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1998b). Such a scenario poses a significant problem when trying to establish backscatter values for particular tree components. For example, due to the open canopy C-band wavelengths are able to penetrate the top and volume of the canopy and even the ground litter returning a backscattered response which is not representative of the interaction occurring at the top of the canopy. Furthermore, canopy gaps may facilitate direct backscatter from the larger branches, ground or understorey layer (e.g., grass and shrubs). This may occur as a function of the incidence angle, where shorter wavelengths, which would not usually penetrate to the ground surface, are backscattered from the trunk or ground due to being propagated at larger incidence (i.e.,  $60^{\circ}$ ) and passing through a canopy gap. Alternatively, a SAR wave of the same wavelength, propagated at smaller incidence (i.e.,  $23^{\circ}$ ) may be backscattered directly from the canopy.

#### 4.7 SAR backscatter modelling

Difficulty in interpreting the SAR response of vegetation has prompted theoretical investigations into the interaction of microwaves with plant components and the ground surface. Initially, investigations focused on crops such as corn and sorghum (e.g., water cloud model; Ulaby et al. 1984). However, more recent studies have considered the decomposition of the forest scattering situation, and a number of backscattering models have been developed and applied subsequently to known forest stands.

As examples, studies have been undertaken on the Duke Forest, USA (Kasischke et al. 1994, Wang et al. 1994, Wang et al. 1998), the Northern Experimental Forest of Maine, USA (Ranson and Sun 1994a, b, Ranson et al. 1997, Sun and Ranson 1998) and the Les Landes Forest in France (Beaudoin et al. 1994, Israelsson et al. 1994, Karam et al. 1995). Extensive modelling has also been undertaken at the BOREAS (Boreal Ecosystem Atmosphere Study) site, which is dominated by Jack Pine (Moghaddam and Saatchi 1999). However, all of these

forests have consisted largely of pine species. Models describing the interaction of microwaves with vegetation of the decurrent form (e.g., deciduous species) have proved more difficult to develop and have therefore received less attention. Despite modelling being undertaken of a number of Australian species (i.e., Cypress Pine; Richards 1990, Dong and Richards 1995), few studies have been undertaken employing simulations of Australian woodland communities.

The sensitivity of backscatter to the dielectric constant and structural parameters (Colwell 1983, Moghaddam et al. 1994) has prompted investigation into these parameters for modelling, scattering and absorption of the SAR signal (Dong and Richards 1995). The structural parameters include the size, shape, number and orientation of the scattering elements within the vegetation volume (e.g., leaves and branches) and soil. The dielectric parameters include the moisture content within the leaves and the woody volume of the plant and the underlying soil surface. Through this approach, the dependence upon empirical relationships between SAR backscatter and biomass is reduced as attention is focused on the retrieval of parameters that actually influence the SAR return but from which biomass may ultimately be derived.

# 4.7.1 Continuous Canopy Models

A number of models have been developed, in which the vegetation scattering mechanisms have been modeled using fully polarimetric data (Richards et al. 1987, Ulaby et al. 1990-Michigan Microwave Canopy Scattering Model - MIMICS). These models are derived, consistent with a first order radiative transfer approach and are capable of computing the backscattering coefficient for any receive/transmit polarization. Such an approach treats each component separately, without interaction and does not involve any multiple scattering events.

In response to Richards et al. (1987), it was theorized that if the primary scattering mechanisms do not cause depolarization of the SAR signal, multiple order scattering may be more significant (Richards 1990). Subsequently, the consideration of the depolarizing properties of foliage and twigs through multiple scattering is fundamental. Particular consideration was given to the cylinder-ground double bounce scattering mechanism by Dong and Richards (1995), whereby the forest woody matter were modeled as discrete collections of finite dielectric cylinders. The increase and decrease in inclination of the cylinders produced a decrease in like-polarisation and increases in the cross-polarised response respectively.

# 4.7.2 Discontinuous Canopy Models

MIMICS II was the second generation model which considered open (discontinuous) canopies (McDonald and Ulaby 1993). The location, shape and size of the individual tree crowns are treated as random variables. MIMICS II demonstrates that the influences of the discontinuous crown layer geometries on the SAR return were most prevalent at high frequencies and low incidence angles. This is due largely to the crown transmissivity, facilitating penetration of the SAR signal to the lower levels of the forest.

The Santa Barbara Microwave Canopy Backscatter Model (SBMCBM; Sun et al. 1991, Wang et al. 1993) was also developed for discontinuous tree canopies (i.e., non-interlocking crowns), and combines a single tree backscatter model and a gap probability model. The forest scattering mechanisms illustrated by the SBMCBM are summarised in Equation 4.21.

$$T_t = T_s + T_c + T_m + T_d$$
 Equation 4.21

where,

 $T_s = surface backscatter$ 

T<sub>c</sub> =crown volume scattering

- T<sub>m</sub> =crown-ground multiple path interactions
- T<sub>d</sub> =double-bounce trunk-ground interactions

The model of Durden et al. (1989, 1991), by contrast, is a discrete component model, involving a three-component (branches, trunk and ground) scattering classification to determine the dominant scattering mechanisms at each frequency and polarization. This model assumes that scatterers are distributed in two layers. The upper layer is comprised of branches, which are represented by randomly orientated finite dielectric cylinders corresponding to a  $sin^4\alpha$ distribution, where  $\alpha$  represents the angle about the mean orientation angle with respect to the vertical. The lower layer contains only tree trunks, which are modelled as randomly located vertical dielectric cylinders, which (in the case of the decurrent form) extend into the upper layer. The ground is assumed to be a Bragg rough surface characterised with a first order small perturbation model. Scattering from each layer is calculated using a first order (Born) approximation. The model simulations include contributions from the ground and branch layer and also double bounce from the trunk-ground and branch ground (Figure 4.3).



Figure 4.3 Examples of scattering mechanisms considered within the model of Durden *et al.* (1989)

The wave attenuation through the branch and trunk layers is accounted for by averaging the elements of the forward scattering amplitude matrix over all cylinder orientations, amounting to a distorted Born approximation for the total effect of the vegetation layer on backscattering.

#### 4.8 Mapping biomass

A number of approaches to the mapping of biomass from SAR have been trialled using data from a range of airborne and spaceborne sensors.

Techniques include the use of classification algorithms (Dobson et al. 1995, Saatchi et al. 1997, Saatchi and Rignot 1997, Ranson and Sun 1997, Bergen and Dobson 1999, van der Sanden and Hoekman 1999, Castel et al. 2000), although, a number of studies have considered the use of algorithms for segmenting images prior to classification (Li et al. 1999, Dong et al. 1999). Biomass mapping and subsequent calculation of carbon content in areas subject to clearance or regrowth has been demonstrated using the segmentation algorithm of Dong et al. (1998) and Lucas et al. (2000a, b). The majority of forest mapping research has been undertaken in tropical forest, focussing on primary, secondary and logged over forest areas. HV polarisations have been found to contribute the most for forest type mapping at all frequencies (Saatchi and Rignot 1997, Saatchi et al. 1997, van der Sanden and Hoekman 1999). At the L- and P-band frequencies, the predominance of volume scattering within the forest canopy and the relatively small influence of incidence angle variation on the backscattered HV signal is responsible for the ability to discriminate forest types. Primary forest types were the most difficult to classify (van der Sanden and Hoekman 1999) with LVV and PHH yielding the best results. Saatchi et al. (1997) found the combination of LHH and LHV successful in separating the secondary regrowth from the primary forest, since the disturbed forest has a higher LHH return because of the enhanced double bounce scattering resulting from the clear forest floor and the sparsely distributed trees.

In their investigation of tropical forests, using JERS-1 SAR, Kuplich et al. (2000) concluded that the data were suitable for locating, estimating and mapping the biomass of young regeneration stages of block-logged forest (r=0.77). However, the data were not suitable for locating, mapping and estimating the biomass of regenerating forest that had been logged selectively (r=0.15). These results have implications for the mapping of vegetation in Australia. Much of Australia's vegetation is found in a mixed woodland environment, where considerable heterogeneity exists among species, tree heights, crown widths and the presence of gaps. Furthermore, the combination of this heterogeneity and higher biomass levels, evident in mixed woodlands would certainly impact on the viability of employing JERS-1 SAR.

The SAR return at different wavelengths and polarisations is a function of the overall structure and biomass of vegetation components. For this reason, differences in SAR backscatter may be used to discriminate different types of forests. SAR has the ability to map vegetation types by: a) textural analysis, b)

combination of texture analyses and classification, and c) classification as outlined below.

#### 4.8.1 Textural analysis

Textural analysis of SAR data has been undertaken by a number of studies for the identification of landcover types. The techniques include the calculation of lacunarity indicies (Ranson and Sun 1997, Dong 2000), Grey Level Cooccurrance GLCO (Luckman et al. 1997a, Fransson et al. 1999, van der Sanden and Hoekman 1999) and a variety of texture algorithms (Haack and Beahdol 2000).

### 4.8.2 Texture and Classification

Forest types may be discriminated through a combination of texture analysis and classification (Ranson and Sun 1997, Soares et al. 1997, van der Sanden and Hoekman 1999, Fransson et al. 1999). Results of Soares et al. (1997) confirmed that the addition of texture measures improved the accuracy of classification of agricultural cover themes from SAR imagery. Van der Sanden and Hoekman (1999) found that texture, not backscatter, was the most important source of information for identifying tropical landcover types in high frequency and high resolution radar images.

# 4.8.3 Classification

There have also been many studies adopting solely a classification approach, employing a maximum-a-posteriori (MAP) Bayesian classifier (Nezry et al. 1993, Ranson and Sun 1994b, Saatchi and Rignot 1997, Saatchi et al. 1997, Michelson et al. 2000), parallelepiped classifier (Ranson and Sun 1997) and the back propagation neural network classification algorithm (Michelson et al. 2000). Saatchi and Rignot (1997) employed a unique approach, combining radiometric, polarimetric and textural attributes with subsequent classification. Dobson et al. (1995) used a synergistic approach based on both ERS-1 SAR and JERS-1 SAR data but obtained low levels of classification accuracy due primarily to signal saturation of the C-band signal. The greater dynamic range afforded by the JERS-1 SAR, enabled better discrimination of structural classes. For example, Luckman et al. (1997a) found that C-band data could be used to discriminate between forest and non-forest areas but only in dry conditions.

A classification algorithm (Mapveg), developed by Tony Freeman at JPL isolates the different SAR scattering mechanisms according to cover type. Mapveg is used to conduct a first-level classification of AIRSAR data into simple ground cover types including urban areas, forest, clear-cut and marshlands. The classification algorithm operates by providing estimates of the contributions of surface, double-bounce and volume scattering from the AIRSAR image. These estimates are subsequently interpreted via polarisation signatures of each of the three AIRSAR wavelengths (i.e., C-, L- and P-band).

#### 4.8.3.1 Segmentation

Prior to classification into land cover or biomass classes, segmentation of the SAR imagery has been advocated. Different segmentation methodologies exist, however, the use of the Gaussian Markov random field model (Dong et al. 1999) has been applied to Australian datasets in previous studies (Lucas et al. 1999, 2000a, 2000b). Given that classification is based on the information presented by each pixel, there is considerable room for error, due to the amount of speckle within the SAR image. The speckle is a result of the coherent processing and synonymous with SAR imagery. Classification accuracy can be improved by averaging data, although this technique results in the loss of information within the SAR image. Segmentation is achieved via the Gaussian Markov random field model, since it considers two regions to be different and subsequently, assigns separate segments if one or more of the following condition is true.

- Their first order statistics are different
- o Their second order statistics are different
- Their spatial textures are different.

The segmentation procedure may be applied to all types of SAR imagery (i.e., AIRSAR, JERS-1 and SIR-C), although is computationally intensive. The segmentation procedure, as developed by Dong et al. (1999) is as follows. First, a Frost filter is applied to the image that is to be segmented. As a result, the edges become more apparent, facilitating the identification of the boundaries of the initial segments. Subsequently, original data can be extracted and statistics are calculated for each segment. The segments are closed and then merged. This exists as a flexible approach to segmentation, whereby the main parameters involved may be changed (i.e., the kernel size of the frost filter, the number of segments and the margin of similarity). Outputs from the segmentation process include the mean and standard deviation of the backscatter and also edge The mean values for each segment may then be used as input to images. empirical relationships established between SAR backscatter and biomass. However, the accuracy of the resulting biomass is still dependent upon the viability of these relationships. Alternative segmentation algorithms include those developed by Definiens Ltd. as part of their eCognition software.

4.9 Case Studies: Quantifying the biomass of woodlands in QLD using SAR

Prior to the acquisition of AIRSAR data over Injune in 2000, two case studies were undertaken in the semi-arid woodlands of Queensland. These studies investigated the use of both airborne and spaceborne SAR for quantifying biomass in a woodland environment. Acquisition of field data, remote sensing methodologies, detailed results and recommendations from these studies are outlined in a number of published references (Witte et al. 1998, Lucas et al. 2000a, b, Cronin et al. 2000).

#### 4.9.1 Case Study 1: Injune

This investigation (Witte et al. 1998, Lucas et al. 2000a,b) examined the use of JERS-1 SAR L-band HH data for quantifying the total above ground and

component biomass of mixed species woodlands near Injune in central Queensland.

The relationships established between JERS-1 SAR L-band HH data and biomass are consistent with those obtained in several studies where the greatest contribution was from the trunk rather than the branches and foliage. At Injune, the stronger relationship with trunk biomass was attributed largely to the dominance of C. glaucophylla in many plots, which, unlike most Eucalyptus species, allocates a greater proportion of its biomass to the trunk rather than the branches.

Another consideration is that the foliage biomass of woodlands in Queensland may be better estimated using Landsat TM visible, near infrared and/or mid infrared wavebands as radiation at these wavelengths interacts largely with the foliar components of the canopy. However, further research is required in both cases.

The study suggested that L-band HH backscatter is related only partially to above ground biomass and, at Injune, is best used to estimate trunk biomass. It may be used to estimate above ground biomass although further studies are required. In particular, further plots need to be sampled in low biomass regenerating woodlands. The L-band HH return became asymptotic at approximately 80 – 100 Mg ha-<sup>1</sup>, which may restrict the use of JERS-1 SAR data to lower biomass woodlands.

#### 4.9.2 Case Study 2: Talwood

This study was undertaken by myself (Cronin et al. 2000, Lucas et al. 2000a) and investigated the use of both NASA JPL TOPSAR (C-band and L-band VV and fully polarimetric P-band) data and Space Shuttle Imaging Radar (SIR-C) SAR for quantifying the total above ground and component (leaf, branch and trunk) biomass of woodlands near Talwood in south central Queensland. In comparison to the JERS-1 SAR L-band HH data for Injune, the AIRSAR and also SIR-C SAR L-band VV gave a better relationship with both trunk and branch biomass. The reasons for this improvement are, however, uncertain but could be the result of the reduced occurrence of C. glaucophylla at Talwood, and hence the greater contribution from the branches in Eucalyptus canopies which typically are of larger size and biomass.

The better relationship between C-band VV and both branch and trunk biomass was assumed to be artificial and was attributed partly to the proportional link between woody and foliar biomass, which is inherent for most vegetation. Thus, it is fundamental to understand the within-stand relationships between biomass components when attempting to investigate the interaction of microwaves with vegetated surfaces.

Microwaves at both L-band and P-band were shown to interact equally with both the trunk and the branch biomass. The correspondence in these relationships was attributed partly to the similarity in the size range and orientation of branches and trunks, particularly in the woodlands dominated by Eucalyptus.

Using TOPSAR and SIR-C data, the Talwood study indicated that microwaves of different magnitude interact with different components of the vegetation canopy. The reduction in the strength of the relationship between leaf biomass and the return of microwaves of increasing length suggests that C-band VV wavelengths interact more with the leaves compared to those at L-band and P band. However, as woodland canopies are generally open, interaction with the ground surface may also influence the C-band backscatter and properties such as surface roughness and soil moisture may contribute significantly to the SAR return.

#### 4.9.3 Outcomes

The studies undertaken at Injune and Talwood, using a combination of archival JERS-1 SAR, SIRC-C SAR and TOPSAR data, indicated a sensitivity of SAR data at all frequencies and polarizations to total and/or component biomass. These relationships established also appeared to be relatively consistent between sites and sensors. However, a limitation of these studies is that fully polarimetric data were not available and so a complete insight into the scattering processes involved and the role of SAR data at all available frequencies and polarizations were not provided. Furthermore, the dates on which remote sensing datasets for each site were acquired did not correspond with the dates of field data collection. For this reason, requests were made for the acquisition of fully polarimetric AIRSAR (POLSAR) data during the NASA JPL PACRIM II Mission to Australia. This acquisition, in August, 2000 coincided with a comprehensive campaign of data acquisition by other remote sensing instruments (e.g., lidar, aerial photography) and field data collection (including destructive harvesting). The coincident nature of field and remotely sensed data acquisition would facilitate the derivation of the most accurate estimates of biomass. This is fundamental to the viable interpretation of empirical relationships.

#### 4.10 Summary

This chapter has explored the physical nature of scattering from vegetation. Particular focus has been given to the dielectric properties of the vegetation and soil, as well as the influence of topography and surface roughness. The methods by which these variables are analysed, (i.e., field measurements and preprocessing of remotely sensed data), is considered crucial to the subsequent analysis of the Injune SAR data.

A full review of studies (both empirical and modeling) involving SAR backscatter and its relationship with vegetation biomass was also undertaken. This was important, in terms of the range of biomasses examined, the range of different physical structures involved and the nature of the forests considered (e.g., in terms of density, canopy cover). Generally, studies have directed their focus predominately on the boreal forests of the northern hemisphere. This was beneficial for an understanding of the backscatter interaction with excurrent species at Injune (e.g., Callitris glaucophylla). However, it was evident that there has been very little research undertaken on other forested ecosystems (i.e., woodland), particularly those of mixed species composition.

# **Chapter 5**

# **Study Area**

# 5.1 Overview

This chapter provides a description of the Injune study site, including the exact location of the area in geographic coordinates, as well as it's position relative to neighbouring towns, regional centres and state forests. The climate of the study-site and surrounding environs is examined in terms of monthly rainfall and temperature, including a general description of the typical winter and summer seasons. The geology of the region is described in association with a number of variables. including the vegetation, topography and geomorphology. Soil types within the area are examined, with particular attention being given to moisture holding ability. This is critical in terms of the interaction with the SAR signal. The predominant vegetation types found within the area are described. In addition, a history of the settlement and land use in the area is provided.

# 5.2 Location

The Injune study area (Lat 25° 32', Long 147° 32') is located approximately 650 kilometres north-west of Brisbane, Queensland, in the western part of the Southern Brigalow Bioregion (SBB; Figure 5.1). The study area encompasses several State forests (Crown Land), including Attica, Koolbellup, Simpson and Hillside, while the remaining area consists of a number of leasehold properties. Proximal townships include Tambo, Augathella, Mitchell and Injune, while Roma is the nearest regional centre.



Figure 5.1 Location map of Injune, Queensland Australia

### 5.3 Climate

The Southern Brigalow Belt (SBB) is confined within a bioclimatic zone which is unique globally (Hutchison et al. 1992). The SBB is subject to very high variability of seasonal and annual rainfall, demonstrated by the historical record of extreme rainfall anomolies, which have resulted in severe droughts and massive floods. The climate of the Injune study site may be described as sub-humid to semi-arid warm temperate.

# 5.3.1 Rainfall

The average annual rainfall is 634.9mm. High intensity rainfall occurs, with associated high runoff and summer rainfall dominance, and 42% of the annual mean rainfall is recorded during the summer months, between December and February (Figure 5.2a-b). January is the wettest month, receiving an average rainfall of 90.3mm. Peak rainfall events as high as 364.7mm (in one month), have been recorded, which often result in extensive flooding. Winter months are characterised by low rainfall, with an average of 83.6mm falling over the three month period. August and September are the driest months, recording averages of 24.9mm and 26.1mm respectively. The average number of rainy days is 61.3.

# 5.3.2 Temperature and humidity

Injune experiences cooler temperatures than many of the surrounding towns and regional centres (i.e., Surat and Roma). There is a total average of 1 day per year, reaching above 40°C and a total of 19 days per year where temperatures are less than 0°C. The highest maximum temperature recorded is 43.8°C and the lowest minimum temperature is -8°C.

Summer temperatures typically range from 18°C-34°C, corresponding with very high potential evaporation. Winter is characterised by dry, mild days with

temperatures ranging from 20-34 °C and considerably lower potential evaporation.

Mean absolute humidity is highest in summer but relative humidity is highest in winter on account of the lower temperatures (Galloway 1974). The average relative humidity ranges from 61% at 9am to 37% at 3pm, although varies seasonally.

# 5.4 Topography

A digital terrain model (DTM) of the Injune study-site is shown in Figure 5.3. The study-site is drained by the Maranoa River in the east and the Hoganthulla Creek in the north-west. The Maranoa River drains south-westwards into the Murray-Darling drainage system. This river follows the Maranoa anticline on the eastern side of the study-site.

The sediments located under the study site are fundamental in the determination of the site's topography. These sediments are discussed in detail in Section 5.4.3.

In general, the relief of the site involves an extremely gentle slope, which falls southward. In the north, the hilly and locally mountainous, erosional topography lies between 400-1000m above sea-level (Galloway 1974). This topography has developed on quartzose sediments. At the centre and south of the study-site, the topography consists of rolling to undulating terrain, ranging from low hills and plateaux to plains lying between 200-400m (Galloway 1974).



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2000 b) Figure Annual distribution of the daily maximum and minimum temperatures for Injune, averaged for the period 1925-2000 Figure 5.2 a) Annual distribution of clear, cloudy and rain days and amount of rain fallen (mm) for Injune, averaged for the period 1925-(Bureau of Meteorology 2000).



Figure 5.3 Digital Elevation Model (DEM) of Injune study site with overlaid PSUs (Queensland Department of Natural Resources and Mines 2000).

T CITON	Lithology	Vegetation
Lower and Upper	Quartz rich sandstone	<u>Better sandy soils:</u> Open eucalypt forest an
Jurassic/Cretaceous sediments		poor grass
		<u>Poorer sandy soils:</u> Thick Pine forest or
		scrub
Middle and Upper Jurassic	Calcareous clayey soils	Scrub of Brigalow, belah, bottle tree, wilga
Injune Creek Group		and sandalwood
	Plateaux of basalt and	Open forests of ironbark, box, yamia,
	gabbro	blackboy etc., good grass or with low scrul

#### 5.5 Land Systems

The land systems encompassed by the study site are presented in Figure 5.4. The geomorphology, soil types and vegetation associations supported are indicated. Generally, on the better sandy soils, open Eucalyptus forest occurs whilst Callitris glaucophylla tends to dominate the poorer sandy soils. Within the clay soils, Acacia harpophylla (Brigalow) are commonplace. On the plateaux, open forests of Ironbark etc. occur.

# 5.5.1 Geology

The geology of the area consists of quartz rich sandstone laid down in the Lower and Upper Jurassic/Cretaceous periods (Table 5.1) and also calcareous clayey soils laid down in the Middle and Upper Jurassic Period. In this latter period also, plateaux of basalt and gabbro were formed. The Injune study site encompasses two major classes of material, the quartzose sediments and the fresh labile sediments.

i) <u>Quartzose sediments</u> The predominance of quartz in this rock facilitates a high resistance to deep weathering. Three land systems occur on these quartzose sediments. The QrCp landsystem involves undulating to rolling country with deep sandy-surfaced duplex soils. Cypress pine (C. glaucophylla) forest has developed on the quartzose and micaceous Hutton sandstone.

The QhMe landsystem consists of rock dissected plateaux, rising 20-200m above their surroundings, on which mixed layered eucalypt woodland is found. Located between these dissected plateaux are wide valleys with undulating floors, having deep sands on which smooth-barked apple (Angophora leiocarpa) are commonly found. These comprise the QuA landsystem.

ii) <u>Fresh labile sediments</u> These sediments occur where erosion has removed the deep weathering profile, such that the underlying fresh rocks and Cainozoic sediments are exposed. Where removal has been incomplete, traces of the basal portion of the former deep weathering zone are evident as these support different soils and vegetation. Where the relief is undulating and the soils are moderately deep clays, grassland (SuD) or Mountain Coolibah (Eucalyptus orgadophila) open woodland (SuMc) are found. Smaller area of labile rocks, affected by deep weathering occur on scarps and basalt caps, comprising ShSw. Poplar box (Eucalyptus populnea) open woodland (SrX) occurs in areas of rolling relief on part of the Orallo Formation (Galloway 1974).

### 5.5.2 Soils

The soil types present at the Injune study site are presented in Figure 5.5. The distribution of soil types can also be referenced in terms of land systems (Figure 5.4).

The soil landscapes which are formed on fresh labile sediments have been mapped in three land-systems (SrX, SuMc and SuD), while those formed on quartz sandstones have been mapped on three landsystems (QhMe, QuA and QrCp). The soil families classified within each of the quartz sandstone and fresh labile sediment land systems are described below. These descriptions and the soil distribution map (Figure 5.5) are adapted from those for the Balonne-Maranoa area (Gunn 1974).

i) Brown and grey-brown soils (B) Uniform fine textured soils, including light to heavy clays as well as gradational textures including clay loams grading to medium or heavy clays. Four families have been identified as listed and described below.



Figure 5.4 Land Systems of the Injune study site (Source: Adapted from Galloway *et al.* 1974).

a) <u>Soils formed on weathered zone materials</u> The Ba and Bb soil groups are moderately deep, uniform clay textures, ranging in depth from 65-105cm. They typically occur on middle to lower slopes in undulating country, which support woodland or open forests of E. populnea and/or A. harpophylla and Casuarina cristata. At the surface, the colours range from dark brown to reddish brown and at depth, are dark red. The Bc family are dark brown to dark-grey brown soils, ranging in depth from 80->120cm with a blocky structure evident throughout profiles and in subsoil. Gravel and stone are common at the surface and upper horizons of this soil, occurring on slopes and gently undulating terrain under shrubland of E. populnea, with A. harpophylla present.

b) <u>Soils formed on labile sediments</u> (Bd) These have very similar properties to the soils formed on weathered zone materials (Bc), although they have been derived from fresh or only slightly weathered rocks, integrated with the cracking clays soils of the Cc family. They occur under shrub woodlands dominated by E. populnea.

c) <u>Soils formed on Alluvium</u> (Be) These soils range from dark to very dark brown and grey in colour, with depths exceeding 90cm. They are uniformly silty clay or light to heavy clay textures. They occur mainly under E. populnea woodland.

d) <u>Shallow soils on various rocks</u> (Bf) These soils are usually brown to dark brown with a depth of 60cm or less. Formed from both weathered and fresh materials on crests and upper slopes in hilly terrain, they are uniformly fine soils and sometimes exhibit a gradational texture. They occur under a range of vegetation including woodlands dominated by E. populnea and Eucalyptus melanophloia woodlands.

ii) Cracking clay soils (C) Typically, this group is characterised by uniform medium to heavy clay textures. The six families within the cracking clays soil group have been classified according to differences in the nature and mode of formation of parent materials, micro-relief and effective depth (Gunn 1974). Only two of these families were present at the Injune study-site.

a) <u>Soils formed on weathered zone materials</u> The Cb soil family was present at Injune, ranging in depth from 80 to 150cm. They are similar to the Ca family and are mainly dark grey or brown and less commonly yellowish-red. The surface of these soils is commonly littered with stones and gravel. Brigalow open-forest is a common vegetation association.

b) <u>Soils formed on fresh labile sediments</u> (Cc) These soils range in colour from brown to very dark grey in the upper horizons, which grade to a brown or yellowish-brown. Their depth ranges from 65 to 150cm, with the deeper soils commonly occurring on the lower slopes.

c) <u>Soils formed on alluvium</u> (Ce) In contrast to the above soils, the Ce group are very deep (>150cm). They are grey and brown medium to heavy clays, which are poorly drained, occurring on alluvial plains, which support coolibah open woodland.

iii) Duplex Soils (D) This group contains families belonging to both the quartz sandstones and the labile sediments land-systems at Injune and thus are widely distributed. This group of soils is characterised by the clear boundary between sandy loamy surface horizons and clayey subsoils. Five of the families which are present at Injune belong to two of the sub-groups, which have been classified according to differences in the nature and mode of formation of the parent material at family level.

a) <u>Weakly solonized soils formed mainly on weathered argillaceous</u> <u>sediments</u> (Da, Dc) This group contains soils which have generally clay or sandy-clay loams at surface horizons which grade to dark reddish brown medium to heavy clay subsoils. Both the Da and Dc profiles have depths >90cm, occurring under A. harpophylla, E. populnea and E. melanophloia shrub woodlands. Particularly for the Da family, large areas have been cleared for grain cultivation and improved pasture. The Db family is similar to Da, with the exception of the colour of the subsoil, which ranges from dark grey to dark grey-brown. They occur on gently undulating terrain, which supports E. populnea woodland with a shrub understorey.

b) <u>Soils formed on alluvial materials</u> In comparison to the other duplex soils, these differ with respect to depth, parent material and their location, which is generally in close proximity to streams. The Dh family has a thin (5-25cm) loamy or sandy surface horizon, which overly dark brown to reddish brown clay subsoils. The other families Di and Dj are similar in their morphology; however, Dj soils have a massive sandy surface horizon 30-80cm thick. These soils occur under low-open woodland of E. populnea, with Leopard wood (Flindersia maculosa) and C. glaucophylla being present.

c) <u>Soils formed on quartzose materials</u> This classification encompasses two soil families (Df, Dg), which are distinctive due to their thick (38-76cm), massive sand to sandy loam surface horizons (Gunn 1974). The subsoils are blocky and hard, ranging in colour from yellowish brown to yellowish red. Both support associations of E. populnea, E. melanophloia and C. glaucophylla, with an understorey of the same species. iv) Massive Earths (E) This group features gradational texture profiles, whereby the clay content increases with depth, while the massive structure, maintains an earthy or porous structure. Those soils encountered on the Quartz sandstones have sandy to sandy clay loam surface horizons, usually dark brown to dark reddish (upper 60cms) which grade to light and medium clays in the sub-soils. The vegetation associations with each of these massive earth soil groups are Ea (Mulga forest or woodland with scattered E. populnea and E. melanophloia) and Eg (Woodlands of mulga, scattered with E. melanophloia and E. populnea).

v) Uniform sandy soils (F) This group demonstrates a uniform sand to loamy sand texture and can be divided into two groups.

a) Soils on transported materials which are formed via transported materials on levees near major streams. Surface horizons are dark brown to red, grading to reddish brown and yellowy red. They are generally more than 150 cm deep, with clayey D horizons at depths of 105cm and greater. Vegetation associations include Fa (E. melanophloia and C. glaucophylla open forest).

b) Soils formed on quartz sandstone involve soils that have usually formed in situ. These soils are usually dark brown with Fc having a depth to bedrock of 35-80cm, occurring on crests and upper slopes in undulating to rolling terrain, while Fd is 115->150cm from the bedrock. Vegetation associations include Fc (open forest or woodland dominated by C. glaucophylla or woodlands with E. melanaphloia) and Fd (open forest dominated by C. glaucophylla).

vi) Skeletal soils (G) These soils (Ga) are typically shallow and sandy, underlain by weathered zone materials or sandstone at depths not exceeding 30cm.

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### 5.6 Natural vegetation

The natural vegetation of the region consists predominately of grassland, low open woodland, open woodland, woodland and open forest (Galloway 1974). The distribution of vegetation associations within the study site is demonstrated in the land systems map (Figure 5.4).

# 5.6.1 Pasture Lands

The Pasture Land's classification and descriptions have been included in this section, since the pasture plants, which are predominately perennial grasses, commonly comprise the dominant vegetation associations present at the Injune study site. Furthermore, it is these perennial grasses that are subjected to the indirect impact of clearing (Section 5.7.2). The Land Systems (Figure 5.4) encompassed by the Pasture Lands are shown in brackets.

# a) Down Pasture Lands (SuMc)

This is tussock grassland, which is treeless or has only open stands of trees (e.g., coolibah Eucalyptus microtheca), with no shrubs. The dominant grass is the common curly Mitchell grass (Astrebla lappacea) with minor hoop and bull Mitchell grasses (A. elymoides and A. squarrosa).

# b) Brigalow-Belah ((S)uXB)

This classification involves open forest of Brigalow (A. harpophylla) and Belah (C. cristata), as well as open woodlands with these species comprising the understorey. There exists a distinct ground flora, consisting of short perennial grasses and forbs. However, where there is a dense upper strata of trees, the ground cover is minimal.



Figure 5.5 Soils of the Injune study site (Source: Adapted from Gunn 1974).

In terms of grazing, the carrying capacity of this pasture land is low. Despite being palatable and nutritious for stock, the low density of the Brigalow is responsible.

#### c) Box Pasture Land (SuMc, (S)uX, AX)

The Box Pasture land exists as the most extensive of the pasture lands. The vegetation associations present include, woodland of poplarbox (E. populnea) and silver-leaved ironbark (E. melanophloia), as well as a number of mid-height grasses. There is also a prominent shrub presence. Most commonly, these include sandalwood (Eremophila mitchelli), which is totally unpalatable.

# d) Wire grass Pasture Land (QhMe, QuA, QrCp)

This pasture land exhibits a lower carrying capacity than the Box Pasture Land. It has sparser and less palatable grasses. Undisturbed, there are dense tree layers of Cypress pine or Bull oak (Casuarina luehmannii), which don't allow much ground flora to survive. Poplar box-cypress pine woodland occurs on the harder setting soils.

# e) Mulga Pasture land (AX)

The stands of Mulga (Acacia aneura) within this Pasture Land are often quite dense, with a subsequent low ground cover (Pedley 1974). Due to the value of Mulga as a fodder species, management involves the clearing of enough mulga, in order to promote ground cover. This classification also comprises a number of pasture species, which are common with the Box Pasture lands; however, the ground cover is considerably lower for the Mulga lands. Pedley (1974) describes the most common species as mulga grass (Neurachne mitchelliana), Aristida jerichoensis, A. leichhardtiana, mulga oats (Danthonia bipartita), silverspike grass (Digitaria brownie) and woollybutt grass (Eragrostis eripoda). Generally, this ground cover has been modified by grazing, such that many of the above species have been replaced by wire grasses.
#### 5.6.2 Grassland.

The grasslands consist primarily of Mitchell grass, characterised by a basal cover of about 3%, although cover is extremely variable.

#### 5.6.3 Low Open Woodland.

Dominant overstorey species include leopardwood (F. maculosa), whitewood (Atalaya hemiglauca) and brigalow (A. harphophylla), occurring on fine textured soils.

When disturbed, the structure and composition of these woodlands is altered. For example, regrowth brigalow can dominate extensive areas and, with a low branching habit, can attain densities of more than 25,000 stems (suckers) per hectare (QLD DPI 1984). Individuals taller than ~ 5 m tend to produce a palisade of stems, originating from one or two bases at ground level. This later stage of regeneration, commonly referred to as whipstick brigalow, is typically of lower density with 5,000-20,000 stems per hectare (Johnson 1964). Brigalow belongs to the mallee classification, commonly forming large thickets known as 'Brigalow scrub'.

#### 5.6.4 Open woodland

Open woodland is defined as woodland with less than 10% canopy cover and a height of 10-16m. Dominant overstorey species include poplar box (E. populnea), Coolibah (E. microtheca), Smooth Barked Apple (A. leiocarpa) and a high proportion of Silver-leaved Ironbark (E. melanophloia). Common understorey shrubs include Wilga (Geijera parviflora) and River Myall (Acacia penninervis). The E. populnea community occurs on duplex and cracking clay soils, derived from slightly weathered sediments (Galloway 1974). The woodland floor is generally not home to dense swards of tussock grasses, largely due to the relatively low soil fertility and low rainfall (Fensham 1997).

#### 5.6.5 Woodland

Defined as having a canopy cover of 10-30%, woodlands are considered to bridge the gap between grasslands and forests. The dominant overstorey species is E. populnea, attaining heights of 10-20m and having a density of 50-200 trees per hectare. E. melanophloia has also been found to occur in this stratum. The shrub layer consists of E. mitchelli and occurs on mainly duplex soils and massive earths. The shrub layer ranges from open to dense, with up to 1200 plants per hectare (Galloway 1974).

#### 5.6.6 Open Forests

In many circumstances, communities of A. harpophylla have experienced disturbance up to 50 years ago and as a result, resemble low, open woodland, rather than open forest. However, the undisturbed A. harpophylla communities are found on cracking clays and the brown and grey-brown soils and are characterised by a layered forest, densely populated by A. harpophylla, approximately 10-15m in height. The occasional E. populnea occurs with the A. harpophylla layer or may be an emergent of up to 22m tall. The shrub layer, consisting of either E. mitchelli or G. parvivflora, is common and approximately 2.5-6m in height.

#### 5.7 Landuse History

#### 5.7.1 Post-European settlement

The advance of pastoralists and settlers into the Hunter Valley by 1825, served as a springboard for the occupation of the Queensland Brigalow Belt. Between 1840 and 1861, colonisation of the entire Brigalow domain took place. The onset of the gold rushes in 1851 in New South Wales provided additional markets for the livestock and this enhanced the rate at which squatters were settling in this area. The squatters sought the grasslands, the grassy woodlands and the grassy open forests, preferably with river frontage for their stock. The Brigalow scrub, however, was regarded by the squatters as negative space, due to it's unpalatability for stock and their undesirable vegetative associations, such as the prickly pear.

settlement, grazing has expanded considerably following the Since introduction of beef cattle, sheep and rabbits to the region. Stock has been grazed primarily on natural pastures but many areas of woodland have been cleared for pasture creation. Periods of drought and the associated decline in the carrying capacity of the land also increased the need for pasture improvement and creation, through clear felling or ring barking or growth of fodder crops. Continual periods of low wool prices and substantial developments in machinery since 1945 have also resulted in clearance and, more recently, the expansion of cereal cropping and the emergence of cotton cultivation. In communities of woody species, such as the open-forest of Brigalow, high grazing pressure is leading to a reduction in ground cover to the point where a fire would not be supported, thereby altering the dynamics of the ecosystem. All of these activities are likely to increase the pressure on the surviving woodlands of the Injune area.

During the recent spate of clearing in Queensland, the study area experienced substantial loss of woodlands, largely in discrete and contiguous blocks. Even during the field campaign in 2000, significant areas of woodland were being cleared. Crop cultivation necessitates the total clearance of the vegetation, so as a result, aside from some scattered trees along boundary lines; each paddock is totally cleared of woody vegetation. This prevents farm machinery being impeded during crop cultivation and harvesting.

#### 5.7.2 Clearance regime

The impact of clearance on the biomass of the region is described according to the Pasture Lands. The Land Systems included in each of the Pasture Lands are indicated in Section 5.6.1. The Downs Pasture Lands is characterised by tussock grassland and in some areas open stands of Coolibah (Eucalyptus coolabah). As a result, it can be cleared rapidly and cultivated. Following clearance, the Brigalow-Belah Pasture Land experiences the disappearance of the common grasses and forbs, which is thought to be a result of the increase in light intensity. In areas where Brigalow has been cleared, then burnt, the rapid suckering from the root butt occurs, resulting in a dense stand that excludes most other plant growth. Often, if sheep are left to graze on the emerging suckers, then the regrowth may be controlled to an extent.

The removal of tree and shrubs from the Box Pasture Lands results in rapid regrowth of poplar box (E. populnea) and sandalwood (E. mitchelli). A large increase in herbage is also a consequence of tree and shrub removal, as long as the soil is left undisturbed. Within the Wire grass Pasture lands, an increase in fibrous grasses, unpalatable to stock, is the consequence of clearing. Also, following the clearance of White Cypress Pine (C. glaucophylla), almost pure, dense stands of wire grass is the common replacement.

#### 5.8 Summary

In addition to descriptions of the locality of the study site, in terms of neighbouring national parks, towns and regional centres, this chapter has explored the nature of the climate and the surrounding physical environment at Injune.

The study-site experiences a predominance of summer rainfall, low relief and soils ranging from uniform sandy loams to heavy clays. Generally, the better sandy soils support open eucalypt forest, while C. glaucophylla tends to dominate the poorer sandy soils. The study-site is dominated by the Qu Cp land system, which is characterised by undulating terrain, supporting C. glaucophylla open forest on uniform sandy soils and duplex soils with thick, sandy surface horizons. The dense tree canopy of C. glaucophylla does not facilitate the growth of any significant ground flora. Open woodland, dominated by A. leiocarpa is also common throughout the study-site.

## Chapter 6

# Acquisition and Preliminary Analysis of Field Data

#### 6.1 Overview

For the Injune study area, field data were collected primarily to quantify the structure, biomass and species/community composition of woodlands at Injune and to scale-up these and related attributes to the local landscape using finer (< 1 m) spatial resolution airborne remote sensing data. This chapter describes the overall sample design and the subsequent methods of field data collection. The acquisition, registration and interpretation of large scale (1:4000) stereo aerial photography (LSP) are also outlined, particularly as these photographs played an integral role in the sampling.

Field data collection occurred in two stages. In the first stage, a range of data relating to woodland structure and species composition was collected from 34 plots considered representative of a range of woodland types and growth stages. In the second stage, destructive harvesting of selected trees was undertaken to derive site and time-specific estimates of above ground and component (leaf, branch and trunk) biomass. Soil data were also collected throughout the field campaign to provide an indication of soil type and particularly moisture content.

#### 6.2 Sampling Design

Prior to the acquisition of field and remote sensing data, several approaches to sampling the landscape at Injune were reviewed. In designing the sampling, the following factors were considered.

- 1) Knowledge of the species composition, structural diversity and biomass of the woodlands was relatively limited, particularly given the rapid rate of clearing in recent years and the lack of comprehensive and up-to-date vegetation maps. A stratified sampling approach might therefore be difficult to implement due to this lack of prior knowledge.
- 2) The basic sampling unit would necessarily be constrained by the extent of coverage to be provided by 1:4000 LSP, but also by the area of overlap (~ 920 m width and 150 m overlap) within stereo pairs. Constraints would also be imposed by the characteristics of other observing sensors and their supporting platforms (light aircraft, helicopters) particularly in terms of swath width, flying height, direction of flight and flying times.
- 3) A requirement for unbiased sampling.

Based on these considerations, a sampling scheme for the 40 x 60 km study area was proposed which allowed the acquisition of LSP across a systematic grid of 150 (10 columns and 15 rows) 500 x 100 m Primary Sampling Units (PSUs), with each PSU centre located 4 km apart in the north-south and east-west directions. Each PSU was positioned to encompass the area of LSP overlap (Figure 6.1). For the area covered by each PSU, sampling by other fine spatial resolution remote sensing data (e.g., Compact Airborne Spectrographic Imager (CASI) and LIght Detection And Ranging (Lidar) could also be undertaken. The scheme also proposed the division of each of the 150 PSUs into 30 Secondary Sampling Units (SSU), 50 x 50 m (0.25) in dimension (Figure 6.2a) and could be numbered progressively by row from top left (1) to bottom right (30). Based on this scheme, the equivalent of 4500 0.25 ha (i.e., 1125 ha) would be sampled by both PSUs and SSUs, which collectively represented 0.46 % of the 240,000 ha study area.

#### 6.3 Acquisition of aerial photography

For each of the 150 PSUS, and using pre-defined coordinates, 1:4000 LSP (in negative format) were acquired on the 11<sup>th</sup> July, 2000 by QASCO Surveys Pty. Ltd, on behalf of the Queensland Department of Natural Resources and Mines Landcare Centre. Photographs were taken using an RC20 large format photographic camera from late morning to mid afternoon. The effective swath width was 920 m with a 60 % (50 ha) overlap corresponding to the PSU. For each photo principle point, GPS coordinates were recorded to within a nominal precision of  $\pm$  20 m absolute location. As 150 PSUs were sampled, 300 frames of photographs were obtained. Within each frame, Primary Photo Plots (PPPs; Figure 6.2b) were established over an area of 800 x 800 m (64 ha). Examples of the aerial photographs are given in Figure 6.3.

#### Chapter 6 Acquisition and Preliminary Analysis of Field Data



Figure 6.1 The systematic grid of aerial photographs (black squares) and Primary Sampling Units (PSUs, white rectangles) arranged in 10 columns and 15 rows. Each PSU was 150 x 500 m in size and numbered consecutively from top left (1) to bottom right (150), as indicated in the overlay



Figure 6.2 The location and organisation of a) Secondary Sampling Units (SSUs) within the Primary Sampling Units and b) 800 x 800 Primary Photo Plots (PPPs), using PSU 58\_24 as an example



Figure 6.3 Example of true colour stereo aerial photographs centred over Primary Sampling Units a) 111 and b) 138

6.3.1 Initial interpretation of Large Scale Photography (LSP)

Hard copy production photo prints of the LSP were provided to the Queensland Department of Natural Resources and Mines where Aerial Photo Interpretation (API) was undertaken by Kerstin Jones prior to the field campaign (late July/August, 2000). Each photograph was overlain with an acetate sheet and recognised communities were then delineated and attributed with the following information (Table 6.1).

- a) Species/communities, including the three dominant species and broad understorey type
- b) Ecological maturity (particularly Eucalyptus species)
- c) Structural characteristics (e.g., stand height and crown cover)
- d) The type of disturbance and the level of severity

Table 6.1Attributes associated with polygons mapped from 1:4000 Large Scale<br/>Photography (Jones 2000)

Attribute		
	Classes	
Non-forest type	8	
Forest type (based on dominant species)	3	
Growth stage & proportions (dominant, trace to non-assessable)	6	
Average stand height	3	
Crown cover percentage	4	
Understorey type	5	
Disturbance	13	
Severity of disturbance	4	
Presence of locked up Callitris glaucophylla	3	
Physical features	4	
Road/track access	3	
API Confidence	3	

Using this information together with available Landsat TM data and preliminary biomass maps generated previously using Japanese Earth Resources Satellite (JERS-1 SAR) data; locations for field sampling were identified.

A 1 ha grid (i.e., equivalent to the PPP) was then overlain on the centre of each of the PSUs. In addition to the classes derived from the polygon mapping, each 1 ha cell was also attributed with classes of landuse (14 classes), landcover (12 classes), regeneration (% of grid cell) and stream, water body and road characteristics. A full description of the API, the API decision pathway and associated methodology is outlined in Jones (2000). The limitations involved with this methodology are also discussed.

6.3.2 Selection of Primary and Seconday Sampling Units (PSUs and SSUs) On the basis of the API, broad woodland types were ranked according to area and PSUs containing the most abundant types were identified. For each of these woodland types, the PSUs selected were divided subsequently according to whether they contained either young, early mature or mature/overmature forests. The final selection of 12 PSUs for sampling was based on accessibility. In most cases, these PSUs contained several woodland types at different stages of regeneration. Therefore, within these PSUs, a total of 34 SSUs (collectively representing the main woodland types and their regeneration stages) were selected randomly for subsequent field sampling.

6.4 Acquisition of field data within Secondary Sampling Units (SSUs) In late July/August, 2000, a field campaign to the Injune study area was undertaken with the objective of measuring key attributes relating to the species/community composition, structure and biomass of the woodlands. All field measurements were undertaken within the 34 SSUs. The data were also collected to further support the interpretation of aerial photographs as well as Lidar and CASI data, acquired over the entire PSU grid during and immediately following the field campaign.

#### 6.4.1 Plot layout

The southwest corner of each of the 34 SSUs was located in the field using predefined geographical coordinates and through reference to enlarged copies of colour aerial photographs. Once located, a 50 x 50 m plot (equating to a single SSU), aligned in a north-south direction, was established. Within this plot, 50 m tapes were laid out to produce a 10 x 10 m grid to guide the subsequent location of trees for measurement. 50 m tapes running in the north-south direction and located at 10, 25 and 40 m from the south west corner in the east-west direction were used for recording Foliage Projected Cover (FPC), Ground Cover Percent (GCP), canopy cover and soil moisture. These are referred to as the primary transects (Figure 6.4).

Within each plot, the location of all trees > 10 cm in diameter (at breast height) was recorded electronically by first placing reflectors at each of the plot corners and then using either a GEOSCAN or CENTURION Laser Rangefinder to record the distance and angle from each tree to the nearest visible reflector. Using this approach, the location of trees in UTM coordinates could be established subsequently. Trees 5-10 cm in diameter were located by reading the x and y distances (in cm) from 50 m tapes placed perpendicularly (at 10 m intervals) across the entire plot. The cover and height of trees and shrubs < 5 cm in diameter was estimated within five 10 x 10 m subplots, with four located at a distance of approximately 7.5 m from each of the corners and a fifth located at the centre of the plot.



Figure 6.4 Diagrammatic representation of the 10 m grid, the primary transects and the 10 x 10 m subplots within each SSU (in this case, SSU 58\_24)

#### 6.4.2 Tree measurements

Depending upon the size of the tree (> 10 cm, 5-10 cm or < 5 cm in diameter at breast height), a number of different measurements were recorded. For all trees > 5 cm, diameter above bark at both 30 cm and 130 cm above ground level was recorded using standard diameter tapes. Measurements at both 30 cm and 130 cm were recorded as either or both were used as input to allometric equations available for estimating above ground and component biomass. Each tree measured was given a unique identification number (TID). Where trees had multiple stems, each stem was measured separately and then associated with a unique stem ID (SID). As an example, a tree with three stems emanating at between 30 and 130 cm above ground level, would have one TID and three SIDs.

For all trees > 10 cm diameter (at 130 cm), the height of the crown top (HT\_TOP), the crown base (HT\_CB) and the first leafing branch (HT\_FB) was measured using a GEOSCAN and/or CRITERION Laser Rangefinder. For all trees 5-10 cm in diameter (at 130 cm), height was estimated using reference measurements (height sticks). For trees < 5 cm in diameter, an average height was estimated. Crown width (m) was measured in both the north-south (CROWN\_NS) and east west (CROWN\_EW) directions by laying measuring tapes beneath the crown.

Regardless of size, all trees measured were identified to species by qualified botanists from Queensland Department of Natural Resources and Mines. Identification to species was considered critical for subsequent and appropriate application of allometric equations for biomass estimation. For all trees > 10 cm in diameter, a number of codes relating to their physical structure were recorded. A code relating to the number of large branches (MB) emanating from the main stem at the first leafing branch was given. Each live tree measured was also associated with a growth stage whilst dead or dying trees were associated with a senescence category (Table 6.2). Full definitions of the growth stages and corresponding illustrations are given in Appendix B. A constraint code (Table 6.3) was given to indicate whether the development of the tree might have been impinged by an external factor (e.g., crowding). As with the growth stage code, the constraint code was assigned partly to assist identification and understanding of outliers in statistical relationships established subsequently with the data. Full definitions of constraint types and corresponding illustrations are also given in Appendix B.

#### 6.4.3 Foliage Projected Cover (FPC) and Ground Surface Cover (GSC)

For subsequent calculation of FPC and ground surface cover (GSC), the presence or absence of canopy and ground material was recorded at 1 m intervals along the primary transects. The recording method, which is described by Specht (1970), uses a PVC tube which is attached to a rod 2 m in length and contains an internal cross-hair. A mirror situated at the base of the tube and at an angle of 45° then enables the operator to record the presence or absence of green leaves or branches in the canopy located vertically above (Table 6.4). Where the rod touches the ground (at 1 m intervals), the ground cover is simultaneously recorded (Table 6.4). From these measurements and for a given length of transect, FPC (in units of percent) is equivalent to the number of green leaf occurrences divided by the number of observations. FPC is generally less than Canopy Projected Cover (CPC), which considers the proportion of canopy material (e.g., branch) occurrences divided by the number of observations. GSC is expressed typically as a proportion of surfaces within the transect (i.e., Ground Cover Percentage, GCP). The FPC data were used subsequently to derive relationships with remotely sensed data. However, the GCP was not used in this thesis, although the data are available.

#### 6.4.4 Photographs of the canopy and individual trees

At intervals of 5 m along the primary transects, colour digital photographs of the canopy were acquired (Figure 6.5), largely to confirm interpretation of FPC data. Digital photographs were also taken of at least every tenth tree (> 10 cm diameter) measured. In some plots (e.g., 142\_13), every tree measured was photographed, largely as reference but also to assist derivation of key structural attributes (e.g., branching angle).

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Code	Growth Stage	Code	Growth Stage
R	<b>Regeneration Phase</b>	Ι	Intermediate Phase
Y	<b>Development Phase</b>	0	Senescence Phase
Ε	<b>Consolidation Phase</b>	<b>S1</b>	Dead – small branches present
Μ	Fully Developed Phase	S2	Dead – major branches or stubs present
L	<b>Deteriorating Phase</b>	<b>S</b> 3	Dead – stem only present

#### Table 6.2Tree growth stage codes

Table 6.3Tree constraint codes

Code	Constraint
Ν	Normal Development
А	Arrested Development
Р	Previous Restriction
R	Current Restriction
TI	Temporary Intermediate Damage
TS	<b>Temporary Significant Damage</b>
LI	Long Term Intermediate Damage
LS	Long Term Significant Damage
U	Unrecoverable Damage

#### Table 6.4Codes used in the estimation of FPC and GSC

Code	Description (for FPC)	Code	Description (for GSC)	
OGL	Green leaf	UGL	Green leaf	
ODL	Dead leaf	UDL	Dead leaf	
LBR	Live branch	UGR-LIT	Grass litter	
OSK	Sky	UBA	Bare soil	
USH	(Understorey) Shrub	TTL GL	Total Green Leaf	
	2		Total Green Leaf	
		GL/SH	<b>Overstorey and Shrub</b>	

#### 6.4.5 Soil Moisture

The preliminary analysis of Time Domain Reflectometery and actual soil measurements is outlined in Section 6.10.

#### 6.4.5.1 Time Domain Reflectometry (TDR)

Within selected Secondary Sampling Units, using a Time Domain Reflectometer (TDR), soil moisture measurements (volumetric water content and the dielectric constant) were recorded at 5 m intervals along each of the 50 m North-South tapes (0 m to 50 m) using a 20cm probe. Thus, 50 measurements were recorded for each SSU, using this method.

#### 6.4.5.2 Actual soil samples

Within each SSU, soil samples were taken for subsequent estimation of soil gravimetric moisture content. These samples were taken at a distance of one metre diagonally towards the centre of the SSU, from the four corners of each plot. Samples were taken at depths of 0-1cm, 1-2cm, 2-3cm, 3-4cm and 4-5cm. Thus, the number of soil samples per SSU totalled 20. The selection of these sampling points was due to the ease at which they could be located within each of the 34 SSUs, as well as providing a reasonable representation of the soil moisture over the entire SSU. The samples were stored in airtight plastic bags until soil moisture analysis was undertaken at UNSW.



Figure 6.5 Canopy photographs taken for SSU 81\_16 for the 10m, 25m and 40m transects

#### 6.5 Destructive harvesting

During late August, and following the plot measurements, destructive harvesting of selected trees at Injune was undertaken for the following reasons:

- 1) To generate new equations for the commercial species Callitris glaucophylla, as only taper functions for estimating volume were available and equations had not been established for estimating leaf and branch biomass.
- 2) To establish whether existing equations for estimating total and component biomass for both E. populnea and E. melanaphloia were applicable for these species at Injune. These equations had been established at site several 100 km distant and in a different season and year.
- To establish equations for estimating the biomass of smaller subcomponents (e.g., branches < 1 cm) to assist subsequent interpretation of SAR data and modelling of SAR backscatter.
- 4) To estimate the water content of different sub-components (leaves, branches and trunks).
- 5) To establish allometrics that use variables (e.g., height) that can be quantified using remotely sensed data as input.

The harvesting was undertaken on site by UNSW, QDNR and BRS in conjunction with the Queensland Department of Primary Industries (DPI) Tropical Beef Centre (TBC), with partial funding from the Australian Greenhouse Office (AGO). Trees selected for harvesting were located adjacent to SSUs within which field data had been collected, as not all of the finer spatial resolution airborne remote sensing (e.g., Lidar, CASI) data had been acquired for the PSUs at the time of harvesting. The sizes of trees harvested were based upon the distributions of diameters observed for each species within all SSUs sampled. Trees harvested were considered 'average' with respect to, for example, vigor and foliage cover. In total, 20 Callitris glaucophylla, 7 Eucalyptus populnea and 5 Eucalyptus melanophloia trees were harvested (Figure 6.6). The structural measurements for each are outlined in Table 6.5.

Table 6.5Circumference, height and crown area ranges for trees destructively<br/>harvested at Injune during August, 2000.

Harvested Species	No.Harveste d	130cm Circumferen ce Range (cm)	30cm Circumferen ce Range (cm)	Height Range (m)	Crown Area Range (m²)
Callitris glaucophylla <sup>1</sup>	20	5.0 - 121.0	7.5 – 135.0	2.4 - 20.6	0.82 - 43.0
Eucalyptus melanophloia <sup>1</sup>	5	18.5 – 144.5	25.5 – 161.7	4.2 – 15.2	1.77 – 38.8
Eucalyptus populnea <sup>1</sup>	7	7.1 – 172.0	7.4 – 194.0	4.5 – 17.8	1.30 - 107.39

<sup>1</sup>The crown area was calculated for the above harvested species using measurements of EW and NS distance recorded immediately below the crown. Crown depth was not recorded although digital photographs of harvested trees were taken.

During the harvesting, the stem of each tree was cut as close to the ground as practicable and tarpaulins were placed on the ground to avoid loss of material occurring, during felling. Once felled, each tree was separated into the different components of leaves, trunk and branches. For the trunks and branches, different size classes (i.e., < 1 cm, 1- 4 cm etc.) were also separated, as illustrated in Figure 6.7.



The trunk was defined as woody material extending from the base to the first major branching. For Eucalyptus species, each trunk was cut (using a chainsaw) into different components (e.g., 10-20 cm, 20-30 cm) with each then weighed (i.e., wet) subsequently using electronic cattle scales available at the harvesting site. In both cases, a sub-sample of trunks within different size classes was removed and the wet weight was recorded. These sub-samples were then packed for subsequentl oven drying. Dead wood (both trunks and branches) was also weighed.

All branches > 1 cm in diameter were divided into different components (i.e., 1-4 cm, 4-10 cm, 10-20 cm etc.) and again weighed (wet) using electronic cattle scales. A sub sample of branches within the different size classes was also weighed wet and similarly packed for subsequent oven drying.

All branches < 1 cm in diameter and their leaves were then cut from the crown and placed on tarpaulins for subsequent weighing (wet) using suspended spring scales. Leaves and branches approximating to 10 % of the total weight were retained. Within this sub-sample, all leaves were stripped from the branches (Figure 6.8) and then both small branches and leaves were weighed (wet) separately using portable electronic scales. Sub-samples of each were then weighed (wet) and packed into paper bags for subsequent oven drying. The subsequent procedure for oven drying is outlined in Section 6.8 and the flow chart in Figure 6.9 outlines the process.



Figure 6.7 Digital photograph of E. populnea (142\_13) showing the distribution of components and sub-components destructively harvested for each tree at Injune.



Figure 6.8 Stripping of leaves from branches of harvested Eucalyptus populnea at Injune, 2000.



Figure 6.9 Flow diagram demonstrating the process of destructive harvesting.

#### 6.6 Sapwood cross-sectional area

For each tree harvested, the sapwood cross-sectional area was also measured (Figure 6.10). The sapwood of the tree is the outer lighter coloured area of the wood surrounding the inner zone of heartwood, which is typically darker in colour. The sapwood is the only living portion of the wood and contains the active water conducting elements. The sapwood cross-sectional area was measured, so as to trial an alternative allometric method, employing the sapwood cross-sectional area as the independent variable in the predictive equation.

The heartwood contains those elements that have lost the connection to the living foliage component and are therefore non-functional. Traverse sections (~3-5cm) were taken at the base of the trunk and also at 30cm and 130cm above ground level. Immediately following felling, the sapwood was discriminated and the width measured from the heartwood based on colour differences and flow of xylem sap. The cross-sectional area (cm<sup>2</sup>) of the sapwood was then determined at the three height levels.

#### 6.7 Deriving basic structural attributes.

From the field data, and subsequent to the field campaign, crown depth, area and volume were calculated. Crown depth to the first leafing branch (CD\_FLB) was calculated using the canopy top height (HT\_TOP) and the height to first leafing branch measurements (HT\_FLB). Crown depth to the crown base (CD\_CB) was calculated as canopy top height (HT\_TOP) minus the height to the canopy base (HT\_CPYB). The space in the crown between CD\_FLB and CD\_CB was regarded as containing branches and no leaves.



Figure 6.10 a) Disc taken at 30cm displaying the cross-section of stem and b) an enlargement of the disc, showing the lighter, orange-coloured sapwood.

b)

a)

#### 6.8 Derivation of total and component biomass

Following harvesting, all sub-samples of harvested components for each tree were oven dried at 105° for three weeks and then weighed, to give the dry weight (kg). This process was undertaken (and the data were subsequently compiled) by Madonna Hoffman at the Department of Primary Industry (Tropical Beef Centre), Rockhampton Queensland. The wet weight of the components and subcomponents weighed in the field (Figure 6.11) was then multiplied subsequently by the dry-weight/wet-weight ratio of the corresponding sample to obtain an estimate of the total dry weight of each tree. Correspondingly, the water content for all components and sub-components was estimated by subtracting the dry weight from the wet weight. For C. glaucophylla, new allometric equations were generated whilst, for E. melanophloia and E. populnea, the biomass was compared against that estimated using existing allometric equations.



Figure 6.11 Weighing leaves (using cattle scales) from one harvested tree

#### 6.9 Stand Visualisation

The Stand Visualization Software (SVS 2000), written by the USDA Forest Service and the University of Wahsington was used to generate three-dimensional, graphic visualisations of the stand components (trees and shrubs). To provide a pictorial representation of the individual species at Injune, a tree-form file was generated. Profile, overhead and perspective views were then generated. These visualisations complemented tree mapping data, by providing a visual summary of the SSUs general structural attributes and were generated for all 34 SSUs (Figure 6.12-6.21).



SVS representations of Secondary Sampling Units a) 23\_15, b) 23\_16, c) 23\_20 and d) 23\_24. Figure 6.12

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Stand Visualization Svs



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#### 6.10 Soil moisture

Gravimetric and volumetric measurements were taken from the Injune PSUs. This information, in addition to soil type and bulk density measurements was fundamental to the parameterisation of the backscatter model (Chapter 11).

#### 6.10.1 Gravimetric Water Content (GWC)

For soil samples taken from the SSUs, the soil moisture (%) was measured using the gravimetric method. In this method, the wet sample (up to 100 g of soil) was first weighed, then oven dried (at 105°C) and subsequently cooled in a desiccator containing active desiccant (e.g., magnesium perchlorate or calcium sulphate) to remove all water, and finally reweighed to determine water loss. The Gravimetric Water Content (Equation 6.1) was determined as:

$$GWC = \left(\frac{Soil \cdot wet \cdot weight - Soil \cdot dry \cdot weight}{Soil \cdot dry \cdot weight}\right)$$
 Equation 6.1

For each depth interval (i.e., 0-1cm, 1-2cm), the average was taken from the four corners of the plot, for each of the SSUs. The Gravimetric Water Content is expressed as a percentage for each of the PSUs in Table 6.6.

#### 6.10.2 Volumetric Water Content (VWC)

The Gravimetric Water Content of the soil was converted to Volumetric Water Content according to Equation 6.2, using bulk density measurements for selected SSUs (Table 6.6) provided by BRS.

$$VWC = GWCx \frac{BD \cdot of \cdot soil}{Density \cdot of \cdot Water}$$
 Equation 6.2

### 6.11 Soil type

As indicated in Chapter 5 (Study Site Description), a range of soil types occurred at Injune. More detailed information on the type of soil was recorded for selected SSUs during a subsequent field visit by BRS (Table 6.6).

PSU	SSU	GWC %/100	Bulk Density (g/cm³)	VWC %/100	Soil Type
114	12	0.06	1.42	0.08	Medium sand
124	19	0.05	1.27	0.06	Sand
81	11	0.04	1.40	0.06	Sand
138	21	0.01	1.46	0.02	Sand
144	135	0.12	1.51	0.18	Medium sand
23	24	0.04	1.47	0.06	-
111	18	0.13	1.43	0.18	Sand
148	1	0.05	1.51	0.08	Clay
131	18	-	1.55	-	Clay
142	2	0.05	1.52	0.07	Clay
142	20	0.07	1.49	0.10	Clay
58	29	0.03	1.47	0.04	Light Clay
59	27	0.13	1.48	0.19	Clay
59	28	0.13	1.48	0.17	Clay

Table 6.6Gravimetric Water Content, Bulk Density and calculated VolumetricWater Content (VWC) with corresponding soil type for selected Secondary<br/>Sampling Units

#### 6.12 Summary

The collection of field data described in this chapter formed the backbone of the research conducted at the Injune study site. Specifically, the inventory data allowed the structure and species/community composition of the woodlands to be assessed. Measurements of tree size were also appropriate for allowing subsequent estimation of total and component (leaf, branch and trunk) biomass from available allometric equations. Individual tree locations were also recorded which allowed their subsequent identification within the finer spatial resolution remote sensing data. The destructive harvesting of C. glaucophylla facilitated the generation of new allometric equations for this species, whilst harvesting of two Eucalyptus species allowed the application of allometrics generated previously and at other sites to be assessed. Information on the

moisture content of the different components of the trees as well as the soil was also provided. Most importantly, harvesting was undertaken at the same time as the AIRSAR data acquisitions. The sapwood cross-sectional width for each of the harvested trees was also recorded, in order to determine the crosssectional area and volume and therefore providing an alternative avenue for calculating leaf biomass.

# **Chapter 7**

# Acquisition and Pre-processing of Remotely Sensed Data

## 7.1 Overview

From August to September 2000, remote sensing data were acquired by several sensors and over a range of scales to support the mapping of woodland species/community composition, structure and biomass. To scale-up field-based measurements of key woodland attributes (e.g., Foliage Projected Cover, biomass), scanning Lidar data were acquired for each of the 150 Primary Sampling Units (PSU). Across the entire PSU grid, the NASA JPL AIRSAR acquired four strips (~12.5 x 80 km) of polarimetric SAR (POLSAR) data. Landsat ETM+ (including data from 2000) and time-series of JERS-1 SAR data were also obtained. This chapter provides an overview of these data, how and when they were acquired, and the key pre-processing steps undertaken before these data were analysed.

#### 7.2 Landsat ETM+ data

For the Injune study area, Landsat ETM+ data was acquired on 2nd September, 2000 in both panchromatic and multi-spectral mode (seven wavebands). Additional time-series of Landsat sensor data were available through the Statewide Landcover and Trees Study (SLATS). Although these time-series data were not processed within this study, derived products of 1991 Foliage Projected Cover (FPC) and SLATS land cover change datasets for 1991-95, 1995-97 and 1997-1999 were provided by the Queensland Department of Natural Resources. The methods used to detect changes in woody vegetation are outlined by Paudyal et al. (1997). The 2000 data were acquired largely to generate comparative datasets of FPC and land cover distributions.

#### 7.21 Preprocessing of Landsat ETM+ data

Through SLATS, geometric correction was applied using the techniques outlined by Armston et al. (2002). All scenes were registered to Universal Transverse Mercator (UTM) Coordinates (Zone 55 South) using the World Geodetic System (WGS 84) Datum. For radiometric calibration, the Landsat ETM+ digital numbers (DN) were first converted to units of at sensor radiance (W m<sup>-2</sup> sr<sup>-1</sup> µm<sup>-1</sup>) using standard calibration coefficients (Danaher et al., 2001). The radiance values were then converted to reflectance (p) using the 6S code developed by Vermote et al. (1997). The conversion was calculated on a pixel by pixel basis using information on the scene corner coordinates, overpass time and acquisition date. Corrections for solar zenith and azimuth angles were also applied. The derivation of the Foliage Projected Cover (FPC) equation involved plotting field measured FPC in multi-temporal NDVI and multi-temporal TM5 feature space and ensuring that sites are representative of the relationship between FPC, NDVI and TM5 for the majority of the scene (Kuhnell et al. 1998). This facilitated the development of a standard second-order polynomial (Equation 7.1) accounting for a continuous range of FPC.

$$FPC(Overstorey + Shrubs) = a + b(NDVI) + c(NDVI)^{2} + d(TM5)$$
  
+  $e(TM5)^{2} + f(NDVI \times TM5)$   
Equation 7.1

Where field data points, together with 12 standard zero FPC points are used to calculate the coefficients a, b, c, d, e and f.

#### 7.3 Scanning Lidar (Light Detection and Ranging)

Lidar is an active remote sensing instrument, mounted either on a small plane or helicopter. During operation, the Lidar directs a near infrared (NIR) laser pulse through a rotating mirror towards the Earth's surface (thereby creating a zig-zag swath). This pulse (which travels at the speed of light) reflects from objects (e.g., tree crowns and the ground surface) and is then received by the sensor. The time-delay between pulse transmission and receipt is related directly to distance to/from the object.

At Injune, and for each of the 150 PSUs, Lidar (laser scanner) data were acquired over a one-week period, commencing on the 24<sup>th</sup> August, 2000, using an Optech 1020 scanning Lidar mounted in a Bell Jet Ranger helicopter. The specifications of the Lidar data are presented in Table 7.1. Data were acquired at a nominal altitude of 250 m, with a swath width of ~ 200 m (centred on each PSU) and a beam divergence of 0.3 milliradians. An east-west flight direction was necessary to allow complete coverage of each 150 x 500 m PSU. At this flying height, a footprint of approximately 7.5 cm was obtained giving an average sample interval of < 1 m. With full differential GPS corrections and an inertial navigation system (INS) that compensated for aircraft pitch, yaw and roll, coordinates with an absolute accuracy of < 1 m in the x and y directions and < 0.15 m in elevation were obtained. The data were acquired under dry and clear conditions. During the time of data acquisition, strong westerly winds prevailed but as the helicopter was travelling in an east-west direction, their influence on the spatial integrity of the data was minimised.

Table 7.1Specifications of the Lidar data acquired over Injune

Nominal Spatial Resolution (m)	1
Nominal Altitude (m)	250
Swath (m)	200
Along track spacing (m)	2.806
Max across track spacing (m)	0.766
Footprint size (m)	0.25
Sampling Intensity (returns/m²)	5/2.15



Figure 7.1 Lidar first and last returns from vegetation and the ground.

a)

The Optech 1020 measured 5,000 first and last returns, which could be associated with both ground and vegetation and also the intensity of each return per second (Figure 7.1). The Lidar were acquired as the difference in distance between the returns from the vegetation and ground can be used to measure the heights of vegetation components, including crown/canopy top height. Furthermore, the frequency of returns at different height levels was considered indicative of the density of crowns and the vertical/horizontal distribution of tree components (i.e., branches, leaves etc.).

#### 7.3.1 Pre-processing of Lidar data

The processing of the Lidar data, was undertaken by the Bureau of Resource Sciences (BRS) and the Queensland Department of Natural Resources (QDNR) and further details can be found in Tickle et al. (2003). From the last Lidar return data, a bare earth Digital Elevation Model (DEM), was generated for each PSU to provide ground reference against which to establish the height of the vegetation. From the point coverage of Lidar returns, a triangular irregular network (TIN) was generated and then transformed into a 1 m grid based on bilinear interpolation methods. Checks were undertaken to ensure that all ground returns had been classified correctly. The relative accuracy of the ground surface DEM was regarded as being < 1 m, considering that many ground features (e.g., tracks) < 20 cm in height were discernible.

The height of the vegetation returns above the ground surface ( $G_{DEM}$ ), measured above mean sea level, and was then calculated using:

Where  $V_f$  represents the first return from vegetation (also measured above mean sea level). In many cases,  $V_f$  and the last return from vegetation ( $V_l$ ) were similar.

From these data, a vegetation DEM was also generated using the same interpolation methods, with ground points assigned a value of zero. To avoid "bell-shaped" vegetation when viewing in three-dimensions, interpolation was achieved, subsequently using only vegetation returns > 2 m.

## 7.4 Compact Airborne Spectrographic Imager (CASI)

For each of the 150 PSUs, 1 m spatial resolution hyperspectral CASI-II data were acquired on 29th August and 1st September 2000. The CASI is a pushbroom imaging spectrograph and was flown in a Cessna Titan VH-EOS, which The data were acquired at a had been modified for atmospheric research. flying height of approximately 500 m and collected in fourteen wavelength regions (12 bit) covering the visible and near infrared (NIR) components of the electromagnetic spectrum (Table 7.2). During the overflights, base stations were established near PSU 124 (Northing: 543460, Easting: 7157140) and also Mt Owen Airfield (Northing: 7178000, Easting: 559000). CASI Position and Orientation System (POS) data were also acquired to compensate for aircraft position and movement. On both days, the CASI acquired data in a north-south rather than east-west direction (as with the Lidar). During the two CASI overflights, one black and one white pseudo-invariant targets (in the form of 4 x 4 m tarpaulins) were each laid out at three separate sites and in open areas for subsequent calibration of the data. The location of each PIF was recorded using a Global Positioning System (GPS).

Additional details regarding the acquisition of the CASI data and its subsequent pre-processing are outlined in a PhD Thesis, currently being prepared by Michelle Paterson (UNSW student). It was deemed unnecessary to include in this thesis, since reference to the CASI data is only made in subsequent chapters, with respect to registration of the associated datasets.

Band	Centre	FWHM <sup>1</sup>	Description
No.	Wavelength	(nm)	_
	(nm)		
1	445.8	9.6	Blue
2	529.6	13.4	Green
3	549.3	11.6	Green peak
4	569.1	9.7	Green
5	597.5	13.6	Green
6	633.5	9.8	Red
7	680.3	7.9	Red
8	695.5	11.8	Red edge
9	713.7	9.9	Red edge
10	732.0	8	Red edge
11	740.6	9.9	Red edge
12	752.1	13.7	Red edge
13	800.2	9.9	Near infrared plateau
14	837.7	23.4	Near infrared plateau

Table 7.2Overview of CASI data acquired over the 150 PSUs, Injune.

<sup>1</sup>For a Gaussian distribution, full width, half maximum (FWHM) approximates the width across the profile when it drops to half of its peak (or maximum) value.

# 7.5 Airborne Synthetic Aperture Radar (AIRSAR)

On the 31<sup>st</sup> August, 2002, the NASA JPL AIRSAR, on board a DC-8, acquired fully polarimetric (POLSAR) data over the Injune study area. During the overflight, 148 of the 150 PSUs were imaged. Data were also acquired south of the PSU grid such that larger areas or regenerating vegetation (e.g., Brigalow scrub) could be included in the subsequent analysis.

The POLSAR data were acquired in four parallel strips (length and swath width approximating 80 km and 12.5 km respectively) in a "race track" trajectory (Figure 7.2) and from an attitude of ~8294 m. Due to the large amount of data acquired, each strip was subdivided (e.g., cm6367 and cm6376) during subsequent processing by NASA. An overlap of approximately 1 km between adjacent POLSAR strips was accommodated in the flight planning. The POLSAR data were fully polarimetric (HH, VV, HV and VH) and acquired at three frequencies; C-band (5.6cm wavelength or 5.3 GHz frequency), L-band (23.9cm, 1.25 GHz) and P-band (68cm, 0.44 GHz). The incidence angle ranged from approximately 20° to 60°. The four POLSAR images processed covered a total area of 3000km<sup>2</sup> of relatively flat to gently undulating terrain. As the overlap between each POLSAR section is 1km, the total area sampled by POLSAR was 2760km<sup>2</sup>.



Figure 7.2 Location of the flight strips, over which data were acquired by the AIRSAR (POLSAR)

#### 7.5.1 Pre-processing of AIRSAR data

#### 7.5.1.1 Calibration

The eight POLSAR data strips were processed by JPL's Radar Data Centre and provided in multilook (16-look) compressed Stokes Matrix format and in slant range format. The C-, L- and P-band AIRSAR data were synthesised from the multilook (16-look) compressed Stokes Matrix into HH, VV and HV polarisations (as well as total power, TP) and in units of intensity (van Zyl et al. 1987, Zebker et al. 1987). The data were then slant-to-ground range corrected such that the final data were given a nominal azimuth and range resolution of 4.6296 m (i.e., square pixels).

Prior to the application of the Cross-Track Illumination Correction (CTIC) algorithm to each of the AIRSAR strips (Figure 7.2), the incidence angle varies from 26.6°-59.9° (Table 7.3), although no PSUs were observed in the incidence angle ranges of less than 26.6°, between 34.9°-45.8° and 50.5°-57.2°. The variation in incidence angle across each column was therefore considerably less than that across each AIRSAR strip. The sampling design (for acquisition of field and finer spatial resolution remote sensing data) consisted of 150 PSUs arranged in 10 columns. Each POLSAR strip contained three PSU columns, with overlap occurring in columns 3 and 8.

A Cross-Track Illumination Correction (CTIC) was applied subsequently to provide some compensation for incidence angle. First, along track mean values were calculated from each of the images and then plotted to observe the variation in the cross track direction. An n<sup>th</sup> order polynomial trend line was then fitted and used subsequently to remove the variation across the track. These procedures were undertaken within ENVI and on advice from JPL.

Column No.		Incidence A	Angle range	
	6367/6376	6354/6355	6332/6333	6327/6331
1	<b>58.1°-59.9</b> °			
2	47.5°-50.5°			
3	<b>29.8°-34.9°</b>	<b>26.6°-31.0°</b>		
4		<b>45.8°-48.3°</b>		
5		57.2°-58.8°		
6			57.8°-60.0°	
7			<b>46.0°-49.3°</b>	
8			<b>30.3°-33.8°</b>	27.3°-32.6°
9				<b>46</b> .1°- <b>49</b> .0°
10				<b>57.4°-59.0°</b>

Table 7.3AIRSAR incidence angles for each PSU column

## 7.5.1.2 Geometric correction

The eight strips (10 columns) of POLSAR data were subdivided, as indicated in Figure 7.2. As the data were acquired in a "race track" trajectory, four strips required a rotation of 180°. Following rotation, ground control points were established between the Landsat ETM+ data and each of the POLSAR strips. For each AIRSAR strip, between 100 and150 GCPs were established with r.m.s. errors of < 10 m. A third order nearest neighbour polynomial transformation was then applied to register the AIRSAR data, with an output spatial resolution of 5 x 5 m specified. As the terrain was relatively flat or only gently undulating, algorithms for slope angle correction were not applied. Following registration, the 5 m AIRSAR pixels were resampled to 10 m through pixel aggregation. The resulting data were then combined to produce a final mosaic for the Injune area, a subset of which is illustrated in Figure 7.3.

# 7.5.1.3 Extraction and conversion of AIRSAR data

For each of the 4500 Secondary Sampling Units (SSUs), and as indicated in earlier chapters, the composition of the woodland community had been determined through Aerial Photography Interpretation (API) of the 1:4000 stereo colour aerial photography and codes assigned appropriately. Estimates of above ground biomass were also to be generated for each SSU using relationships established with Lidar data (see Chapter 10). Therefore, to establish relationships with laser-derived biomass by species/community, AIRSAR backscatter data (all frequencies and polarizations and both mean and standard deviation) were extracted from the 4500 SSUs contained within the area of the eight flight lines.

Prior to extraction, the intensity data were converted to backscattering coefficient ( $\sigma^{\circ}$ , m<sup>2</sup>m<sup>-2</sup>), defined as the average radar cross-section per unit area of the individual scattering elements such that:

$$\sigma^{\circ}(dB) = 10 \times \log_{10}(\sigma^{\circ})$$
 Equation 7.3

FPC, as derived using relationships established with Landsat ETM+ data (Kuhnell et al. 1998), was also extracted to allow relationships to be established subsequently with SAR backscatter. The relationships observed are described in Chapter 10. Backscatter values were extracted from both CTIC images and non-CTIC images.



Figure 7.3 Proportion of AIRSAR mosaic over the Injune study site, with PSUs 101 to 133 overlain as a vector layer

To evaluate the simulations of the backscatter from selected woodland types using the model of Durden et al. (1989), AIRSAR backscatter data (all frequencies and polarisations) were extracted from SSUs of similar biomass, contiguous with and designated with the same woodland community classification as 9 of the SSUs (81\_11, 111\_12, 114\_4, 58\_29, 148\_16, 23\_15, 142\_18, 144\_19, 114\_12) sampled in the field. Both mean and standard deviation values were extracted from the corresponding AIRSAR strips. As the incidence angle was a key input parameter to the model, the non CTIC AIRSAR data were used for the comparison. The simulation modelling is outlined in Chapter 12.

7.6 Integration of Large Scale Photography (LSP), Lidar and CASI data To ensure co-registration of the LSP, Lidar and CASI data, further registration of the data were required as a errors of a few metres could lead to poor association between, for example, tree height (e.g., as mapped using Lidar data) and species type (e.g., as mapped using CASI data).

As the Lidar were considered most accurate in terms of positioning, selected CASI scenes (incorporating those covering the sampled SSUs sampled in the field) were registered subsequently to the interpolated 1 m spatial resolution Lidar data. To increase the accuracy and speed of registration, images representing the ratio of the CASI bands 11 (740 nm) and 7 (680 nm) were generated. Within these images, brighter values could be associated with the sunlit tops of tree crowns, which corresponded, with the highest points of crowns, as detected using the Lidar data. The images were density sliced to assist this process. By establishing Ground Control Points (GCPs) between these two images, r.m.s. errors of < 1 m were generally obtained.

The 150 PSUs were centred on the 50 ha stereo overlap of each pair of Large Scale Photographs. The main types of woodland were then delineated (by the QDNR) on acetate overlays placed on each of the LSP. For each stereo pair, the hard copy photo prints were then scanned at 600 dots per inch (dpi) to produce digital images. Initially, these images were rectified (by the Bureau of Resource Sciences) using camera parameters and the known location of the Principal Points. For individual SSUs, the photo prints were also enlarged to 1:1000 scale to assist subsequent tree mapping. However, comparison with the Lidar data suggested that these digital LSP were only accurate to  $\pm$  20 m. For this reason, GCPs were established between the LSP and Lidar data resulting in r.m.s errors of < 2 m.



Figure 7.4 a) 1:4000 Large Scale Photography (LSP), b) Lidar and c) CASI data of mixed species woodlands (PSU 138). Smooth barked apples (SBA) are particularly noticeable within the CASI image as these support large crowns with high near infrared reflectance.

The acetates were similarly scanned and the linework was subsequently vectorised and rectified using the same transformations applied to the digital LSP. The resulting GIS layers were then attributed with, for example, dominant and subdominant species and canopy cover. The Large Scale Photography (LSP), Lidar and CASI data for PSU 138 are presented in Figure 7.4.

#### 7.7 Ancillary datasets

A number of digital datasets for the Injune area were provided by the Queensland Department of Natural Resources (QLDDNRM 2000) including ArcInfo coverages relating to the location of roads, State Forest and National Park boundaries, property boundaries and coarser vegetation mapping. As indicated earlier, SLATS land cover datasets (1991-95, 1995-97 and 1997-1999) were provided by QDNR together with FPC datasets for 1991 and could be used to evaluate past and current land use at the Injune study site.

# 7.8 Summary

For spatial assessment and classification of woodland species/community composition, 1:4000 Large Scale Photography (LSP) and 1 m spatial resolution CASI data were acquired over the Injune study area. For quantifying structural attributes (e.g., height and the vertical and horizontal distribution of crown components) and surface elevation, Lidar data were also acquired. These combined datasets facilitated the spatial estimation of total and component biomass as both height and species information was available from the CASI and Lidar data respectively (Chapter 9). These fine spatial resolution datasets and products can therefore potentially be used to reduce reliance on the use of plot-based estimates of total and component biomass and also structural attributes, thereby assisting interpretation of the SAR backscatter data acquired by the AIRSAR.

A Landsat ETM+ scene from 2000 was used to update the time-series and to provide an estimate of FPC at the time of the field campaign. Pre-processing of

the Landat ETM+ data facilitated the estimation of structural attributes (i.e., FPC). Thus, the integration of the above datasets facilitated the derivation of relationships between Lidar-derived biomass estimates and SAR backscatter as well as FPC and backscatter (Chapter 10). Furthermore, extracted non-CTIC AIRSAR backscatter was employed for comparison with backscatter simulated using the model of Durden et al. (1989) in Chapter 12.

Existing data layers provided by QNDRM were used to assist location and interpretation of the remote sensing datasets.

# Chapter 8

# **Biomass Estimation**

# 8.1 Overview

This chapter explores the derivation and subsequent application of the on-site, species-specific allometrics for Eucalyptus populnea, Eucalyptus melanophloia and Callitris glaucophylla, in particular focussing on the estimation of total, component (e.g., leaf, branch and trunk) and sub-component (e.g., branches < 1 cm, 1-4 cm, 4-10 cm) biomass. For the remaining species sampled at the Injune site, existing (if available), or generic equations were used. The independent variables used in these equations are discussed, as well as the relationships between these variables for the harvested species.

Furthermore, all tree data are investigated to ensure compliance to the height and diameter ranges, specified by the allometric equations. The likelihood of errors as a result of the above investigation is explored and any further discrepancies or errors associated with the derivation and application of allometrics and the subsequent estimation of biomass are discussed. Lastly, the use of relationships between sapwood area and foliage biomass is discussed.

# 8.2 Independent Variables

For the Injune study, a range of independent variables was considered for the estimation of total, component and sub-component biomass. Diameter (typically at 130 cm) is a commonly measured attribute in forest inventories. However, many remote sensing instruments are unable to measure diameter directly and for this reason, other attributes such as crown top height and crown area were also considered. These variables also have relationships with other structural attributes (e.g., crown depth).

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#### 8.2.1 Diameter at 130cm and 30cm

As indicated in Chapter 2, DBH, ~ 130 cm above ground level) is generally the prime independent variable used for the estimation of biomass (e.g., Sader 1987, Wang et al. 1994, Keller et al. 2001). However, many equations developed for woodland species in Queensland and New South Wales (e.g., Burrows et al. 1998, Harrington 1979) have used diameter at 30 cm ( $D_{30}$ ) as the independent variable, due partly to the low height level of branching that is typical to many woodland species in Australia. In this study, diameter measurements at both 130 and 30 cm were recorded to allow application of equations generated using both variables, to facilitate comparison of biomass estimated using existing equations and to provide opportunities for future users to apply these equations based on a variety of diameter measurements.

### 8.2.2 Height

The tree (or crown) top height (H) has also been used frequently as an independent variable for biomass estimation (e.g., Harrington 1979), and is particularly appropriate for coniferous species which tend to demonstrate height increases with diameter, even within the mature stages. Height was also considered an important variable to measure given that the LIDAR data provided direct measurements of the height of individual trees. For some equations, both H and D are used together as independent variables, although no such equations were developed for woodland species at Injune. Relationships between H and D can also be used to measure either D or H when one of these measurements is not available, thereby allowing appropriate application of allometric equations.

#### 8.2.3 Crown Area

Crown area (CA) is potentially an important variable for estimating component biomass, particularly in the open woodland environments. There are many species that do not exhibit a strong relationship between H and D. Such species are often characterised either by multiple stems (e.g., A. harpophylla) and a shrub like appearance or have a single stem (e.g., *G. parviflora*) but a large, weeping crown. In many of these cases, relationships with diameter are often ineffective due to, for example, multiple-stems that are difficult to measure individually. Similarly, relationships with H as an independent variable are limited, as the height of the crown may remain relatively constant beyond a certain growth stage, with increases in diameter reflected more in an expansion of the crown. Consequently, the use of H and/or D as independent variables is often inappropriate. However, measurements of CA or foliage cover may provide a better indication of overall biomass and can be used as an independent variable. Even so, the use of CA as the independent variable for estimating biomass is rare.

8.3 Derivation of Allometric Equations via Destructive Sampling Allometric equations for E. populnea, E. melanophloia and C. glaucophylla were generated by destructively harvesting individuals of these species at Injune. As indicated in Chapter 6, C. glaucophylla was harvested primarily to generate new allometric equations, as previously only timber volume equations were available. E. populnea and E. melanophloia were harvested to check the validity of existing equations developed by Burrows et al. (1998) at other locations in Queensland. The new data and equations developed for these latter two species were used primarily to evaluate the utility of those generated previously. Harvesting was also undertaken to better understand the allocation of biomass to different tree components, establish links between structural parameters and biomass, understand the distribution of moisture within trees, and facilitate parameterisation of SAR backscatter models (see Chapter 11). Onsite harvesting was also considered essential such that the best field-based estimates of biomass could be obtained to support the subsequent interpretation of remote sensing data. Individuals for harvesting were selected across the observed range of D and H and included individuals from the regrowth to the old growth stages.

The prediction equations for the total above ground and component and subcomponent biomass (for E. populnea, E. melanophloia and C. glaucophylla) were developed using the ln-transformed dry weight (kg) of the components of the harvested species and their corresponding ln-transformed biometric parameters (i.e., circumference (converted from DBH and/or  $D_{30}$ ) H and CA). The relationship between  $D_{30}$ , H and CA with each of the selected above ground components were determined using linear regression. All equations were generated by the Queensland Department of Primary Industries (DPI) Tropical Beef Centre (TBC), following oven drying and weighing.

#### 8.4 Allometric Relationships Established at Injune

The allometrics derived for the determination of component and subcomponent biomass based on the harvesting (at Injune) of E. populnea, E. melanophloia and C. glaucophylla are presented in Tables 8.1 to 8.5. Tables 8.1 and 8.2 provide the allometrics between tree size measurements and the biomass of major components (e.g., leaves, branches and trunks). Tables 8.3 to 8.5 provide the allometrics for the biomass of subcomponents (e.g., branches of diameter < 1 cm, 1-4 cm, 4-10 cm etc).

For C. glaucophylla, strong relationships were observed between  $D_{30}$ , DBH and also H and the biomass of all major components (Table 8.1). As expected, there was a strong relationship ( $R^2$  often greater then 0.9) between D (both at 30cm and 130cm) and H. A similar strength in the relationships was observed for E. populnea and E. melanophloia, even though fewer trees were harvested. The residual standard deviation (RSD) and sum of squares of the deviations in x (SSD<sub>x</sub>) values were also calculated by the Queensland Department of Primary Industry's Tropical Beef Centre (DPITBC) and used subsequently in applying the anti-logarithmic correction factor (Beauchamp and Olsen 1973) when estimating biomass using these regressions.

For the subcomponents, relationships with  $D_{30}$ , H and CA were variable. For C. glaucophylla, R<sup>2</sup> values exceeded 0.6 in the relationships between circumference and branches < 1 cm, 1-4 cm and 4-10 cm and also the trunk subcomponents of 20 - 30 cm and 30 - 40 cm. Relationships with height were weaker with the exception of branches 1 - 4 cm. However, in the relationships between crown area and branch subcomponents, R<sup>2</sup> values exceeded 0.75 suggesting that crown area represented a useful variable for estimating the biomass of branches for this species. For E. populnea and E. melanophloia, fewer trees were harvested and the relationships should therefore be treated with some caution. For E. populnea, relationships between circumference at 30 cm and subcomponent biomass were generally weak with the exception of trunks 30 - 40 cm ( $R^2 = 0.66$ ) and also branches < 1 cm (R<sup>2</sup> = 0.88) and branches 1 - 4 cm (R<sup>2</sup> = 0.90). For height, the relationships with the smaller branch components were similar, with R<sup>2</sup> values of 0.83 and 0.90 for branches of < 1 cm and 1 - 4 cm respectively. With crown area, relationships were again similar with R<sup>2</sup> values of 0.87 and 0.85 for branches of < 1 cm and 1 - 4 cm respectively. These relationships suggest that D, H or CA can be used to estimate subcomponent biomass of the smaller branches in particular. For E. melanophloia, relationships between D, H and CA and the biomass of branches < 1 cm and 4 - 10 cm were generally stronger that those observed with branches < 1 to 4 cm, with  $R^2$  values generally exceeding 0.75 although the limited sample size (5 individuals) was insufficient to fully establish these relationships.

Table 8.1 (continued on <i>n</i> circumference range of the l diameters at 30 cm (D <sub>30</sub> ) of circumference of below grou	ext page). A harvested tree f 2.4 43 cm. ind samples w	dlometric equation: s was 7.5 135.0 cm ( This provides a m as 62.14 cm. Relation	s generated for C based on measure lean circumferenc 1ships between di	<b>'allitris glaucophy</b> ments at 30 cm ab e of the above gr ameter and height	<b>tha</b> where y = ove ground level ound samples of are also provided	In weight (kg). The ) which translates to 66.1 cm. The mean
	Z	Α	p	${ m R}^2$	RSD	SSDx
x = ln circ at 30cm (cm)						
Total above-ground	20	-5.506	2.491	0.994	0.161	11.847
Leaf	20	-5.061	1.682	0.953	0.310	11.702
Branches (live+dead)	20	-6.582	2.305	0.948	0.439	11.847
Trunk	20	-6.845	2.727	0.991	0.211	11.847
Stem <sup>1</sup>	20	-6.068	2.595	0.993	0.176	11.847
Live Branches	20	-6.711	2.249	0.896	0.623	11.847
$\mathbf{x} = $ ln circ at 130cm (cm)						
Total above-ground	20	-4.316	2.290	0.996	0.135	14.027
Leaf	20	-4.325	1.557	0.944	0.336	14.027
Branches (live+dead)	20	-5.460	2.112	0.943	0.459	14.027
Trunk	20	-5.557	2.510	0.994	0.170	14.027
Stem <sup>1</sup>	20	-4.833	2.386	0.994	0.162	14.027
Live Branches	20	-5.590	2.057	0.885	0.653	14.027

	Z	A	q	$\mathbb{R}^2$	RSD	SSDx
$\kappa = \ln height (m), y = \ln v$	/eight (kg)					
<b>Fotal above-ground</b>	20	-3.279	3.152	0.962	0.394	7.159
leaf	20	-3.509	2.097	0.874	0.503	7.159
<pre>sranches (live+dead)</pre>	20	-4.304	2.825	0.861	0.717	7.159
Trunk	20	-4.471	3.475	0.972	0.369	7.159
tem <sup>1</sup>	20	-3.743	3.280	0.959	0.430	7.159
ive Branches	20	-4.363	2.705	0.783	0.898	7.159
= ln circ at 130cm (cm),	y= ln height (m)					
leight (m)	20	-0.235	0.702	0.965	0.118	14.027
= $\ln \operatorname{circ}$ at $30 \operatorname{cm}$ (cm), y	= In height (m)					
leight (m)	20	-0.578	0.758	0.951	0.139	11.847
= circ at $30$ cm (cm), y=	circ at 130cm (cm)					
irc at 130cm (cm)	20	-1.691	0.895	0.997	1.979	28106.84

<sup>1</sup>Stem = Branch (live + dead) + trunk.

and b) Eu	calyptus melanophloia	in intact w	oodland where	x = height (m) c	or crown area (m	-,, <u>r</u> 1 1 <sup>2</sup> )	
a)	1						
Component	Range	u	А	q	$\mathbb{R}^2$	RSD	SSDx
X = height (m)							
Leaf	4.5-17.8	7	-6.6275	3.2585	0.9561	0.4477	2.0556
Branch	4.5-17.8	7	-6.9087	4.6601	0.9611	0.6013	2.0556
Trunk	4.5-17.8	7	-5.3089	3.9826	0.9397	0.6468	2.0556
Component	Range	u	А	p	$\mathbb{R}^2$	RSD	SSDx
$X = crown area (m^2)$		I					
Leaf	1.3 - 107.4	7	-1.6330	1.0576	0.9528	0.4642	19.4446
Branch	1.3 - 107.4	7	0.2283	1.5146	0.9603	0.6069	19.4446
Trunk	1.3 - 107.4	7	0.7517	1.3079	0.9587	0.5355	19.4446
b)							
Component	Range	ц	Α	q	$\mathbb{R}^2$	RSD	SSDx
X = height (m)							
Leaf	4.2 - 15.2	5	-3.1196	2.0555	0.8808	0.4661	1.1395
Branch	4.2 - 15.2	5	-3.6019	3.3163	0.8603	0.8235	1.1395
Trunk	4.2 - 15.2	5	-3.8690	3.5014	0.9725	0.3630	1.1395

Allometric equations for the estimation of component biomass (y, kg) of the form  $y = a + b \ln x$  for a) Eucalyptus populnea Table 8.2

Sub-component	Range	u	А	q	$\mathbb{R}^2$	RSD	SSDx
X = circumf. at 30 cm (cm)							
Trunk <1 cm*	13.0 - 216.5 cm	11	-2.9694	-0.4435	0.2621	0.5765	5.4010
Trunk 1-4 cm*	7.5 - 135.0 cm	20	-2.5650	0.4573	0.2297	0.6794	11.8468
Trunk 4-10 cm*	7.5 - 135.0 cm	20	-1.9496	0.8901	0.4501	0.7981	11.8468
Trunk 10-20 cm*	36.5 - 135.0  cm	15	-0.3037	0.9778	0.322	0.5806	2.1768
Trunk 20-30 cm*	63.0 – 135.0 cm	11	-15.6206	4.3986	0.6523	0.8492	0.6293
Trunk 30-40 cm*	<b>88.5</b> – 135.0 cm	7	-42.0121	9.7774	0.9585	0.3583	0.1551
Branches <1 cm *	7.5 - 135.0 cm	20	-5.1834	1.5985	0.6188	1.0178	11.8468
Branches 1-4 cm <sup>*</sup>	19.8 – 135.0 cm	17	-10.2257	2.8784	0.9635	0.3356	5.3844

0.6293

0.8543

0.7192

5.1704

-21.3995

11

63.0 – 135.0 cm

Branches 4-10 cm\*

Allometric equations for the estimation of sub-component biomass of the form  $y = a + b \ln x$  for Callitris glaucophylla in intact woodland where  $y = \ln w eight$  (kg) Table 8.3 (continued overleaf).

Sub-Component	Range	u	Α	q	${f R}^2$	RSD	SSDx
X = height (m)							
Trunk <1 cm*	13.0 - 216.5 cm	11	-3.1475	-0.6499	0.3504	0.5409	3.3632
Trunk 1-4 cm*	7.5 - 135.0 cm	20	-2.2150	0.6026	0.2410	0.6744	7.1588
Trunk 4-10 cm*	7.5 - 135.0 cm	20	-1.3691	1.2142	0.5062	0.7563	7.1588
Trunk 10-20 cm*	36.5 - 135.0  cm	15	-0.4543	1.6097	0.3252	0.5792	0.8111
Trunk 20-30 cm*	63.0 - 135.0  cm	11	-15.1556	6.8312	0.5988	0.9122	0.2395
Trunk 30-40 cm*	88.5 – 135.0 cm	7	4.6046	-0.2924	0.0002	1.7586	0.0332
Branches <1 cm *	7.5 - 135.0 cm	20	-3.3329	1.8483	0.4999	1.1658	7.1588
Branches 1-4 cm <sup>*</sup>	19.8 – 135.0 cm	17	-7.7500	3.6721	0.8649	0.6458	2.9698
Branches 4-10 cm*	63.0 – 135.0 cm	11	-10.0476	4.2369	0.1838	1.4565	0.2395
Ch Communit	Dange	s	~	ی۔	ĥ	ריסת	
sub-component	kange	u	Α	D	K <sup>∞</sup>	UCX	XUKK
X = Crown area (m <sup>2</sup> )							
Trunk <1 cm*	13.0 - 216.5 cm	11	-4.2466	0.2492	0.1436	0.6211	9.3743
Trunk 1-4 cm*	7.5 - 135.0 cm	20	-1.2719	0.2667	0.1413	0.7173	21.4287
Trunk 4-10 cm*	7.5 - 135.0 cm	20	0.6078	0.4982	0.2551	0.9289	21.4296
Trunk 10-20 cm*	36.5 - 135.0  cm	15	2.9933	0.4009	0.2511	0.6102	10.0989
Trunk 20-30 cm*	63.0 - 135.0  cm	11	0.3491	1.4547	0.4484	1.0695	3.9551
$Trunk 30-40 \ cm^*$	88.5 – 135.0 cm	7	-3.7158	2.4457	0.6139	1.0929	1.5874
Branches <1 cm *	7.5 - 135.0 cm	20	-1.4039	1.3106	0.7524	0.8202	21.4295
Branches 1-4 cm*	19.8 – 135.0 cm	17	1.7834	1.6570	0.8719	0.6288	14.7031
<b>Branches 4-10 cm*</b>	63.0 – 135.0 cm	11	-3.9744	2.2052	0.8223	0.6797	3.9551
*Components measurements bas	ed on diameter.						
Table 8.4 (continued overleaf).

Allometric equations for the estimation of sub-component biomass of the form  $y = a + b \ln x$  for Eucalyptus populnea in intact woodland where  $y = \ln$  weight (kg)

ub-Component	Range	u	A	q	$\mathbb{R}^2$	RSD	SSDx
= circumf. at 30 cm (cm)							
ranches <1 cm*	13.5 – 194.0 cm	7	-5.5547	1.6194	0.8784	0.6618	6.0338
ranches 1-4 cm*	13.5 – 194.0 cm	7	-8.0697	2.3745	0.9034	0.8513	6.0337
ranches 4-10 cm*	74.0 – 194.0 cm	5	-6.7817	2.1491	0.2956	1.3158	0.4720
ranches 10-20 cm*	117.0 – 194.0 cm	4	5.7003	-0.1608	0.0094	0.4665	0.1592
ranches 20-30 cm*	123.0 – 194.0 cm	က	7.3785	-0.4765	0.0415	0.7997	0.0610
runk 20-30 cm*	74.0 – 131.0 cm	4	13.4623	-2.0196	0.0820	2.1541	0.2034
runk 30 – 40 cm*	117.0 – 194.0 cm	4	-7.0166	2.5046	0.6597	0.5075	0.1592

Table 8.4 (continued).	Allometric equations for th populnea in int	ne estima act wood	ttion of sub-com land where y =	ıponent bioması In weight (kg)	s of the form y =	= a +b <b>ln</b> x for Eu	calyptus
Sub-Component	Range	u	Α	q	$\mathbb{R}^2$	RSD	SSDx
X = height (m)	)						
Branches <1 cm*	13.5 - 194.0  cm	7	-5.3267	2.6959	0.8294	0.7840	2.0556
Branches $1 - 4 \text{ cm}^*$	13.5 - 194.0  cm	7	-8.0697	2.3745	0.9037	0.8513	6.0337
Branches 4-10 cm*	74.0 – 194.0 cm	J.	-2.2557	2.0729	0.0605	1.5197	0.1038
Branches 10-20 cm <sup>*</sup>	117.0 – 194.0 cm	4	31.4192	-9.2397	0.0549	0.4557	0.0003
Branches $20 - 30 \text{ cm}^*$	123.0 – 194.0 cm	3	60.1547	-19.1928	0.0352	0.8023	0.0000
Trunk 20-30 cm*	74.0 – 131.0 cm	4	8.1083	-1.4802	0.0211	2.2244	0.0976
<b>Trunk 30-40 cm*</b>	117.0 – 194.0 cm	4	-123.7328	44.9807	0.3779	0.6862	0.0003
Sub-Component	Range	u	A	q	$\mathbb{R}^2$	RSD	SSDx
X = crown area (m <sup>2</sup> )							
Branches <1cm*	13.5 – 194.0 cm	7	-1.2553	0.8962	0.8670	0.6922	19.4446
Branches 1-4 cm*	13.5 – 194.0 cm	7	-1.6680	1.2801	0.8464	1.0753	19.4446
Branches 4-10 cm*	74.0 – 194.0 cm	5	-0.7108	1.1012	0.3926	1.2219	2.3871
Branches 10-20 cm*	117.0 – 194.0 cm	4	4.9113	-0.0008	0.0000	0.4687	0.5700
Branches 20-30 cm*	123.0 – 194.0 cm	S	5.1210	-0.0272	0.0002	0.8167	0.0922
Trunk 20-30 cm*	74.0 – 131.0 cm	4	7.6323	-0.9943	0.1525	2.0698	1.5595
Trunk 30-40 cm*	117.0 - 194.0  cm	4	-1.2855	1.5885	0.9501	0.1943	0.5700
*Components measurements ba	sed on diameter.						

	intact wo	odland w	/here y = ln wei	ght (kg).			
Sub-Component	Range	u	А	p	$\mathbb{R}^2$	RSD	SSDx
X = circumf. at 30 cm (cm)	)						
Branches <1cm*	25.5 - 161.7  cm	5	-5.1939	1.6320	0.9425	0.3323	2.0372
Branches 1-4 cm*	25.5 - 161.7  cm	5	-2.8145	1.0354	0.4054	1.0333	2.0372
Branches $4 - 10 \text{ cm}^*$	44.0 - 161.7  cm	4	-7.1270	2.2658	0.8049	0.7877	0.9972
Trunk 20-30 cm*	58.0 – 161.7 cm	3	-15.0095	4.0605	0.6383	2.2164	0.2629
Sub-Component	Range	u	А	q	${ m R}^2$	RSD	SSDx
X = height (m)	)						
Branches <1 cm*	25.5 – 161.7 cm	5	-3.0205	2.0065	0.7968	0.6244	1.1395
Branches 1-4 cm <sup>*</sup>	25.5 - 161.7  cm	5	-2.4233	1.7037	0.6140	0.8325	1.1395
Branches 4-10 cm <sup>*</sup>	44.0 - 161.7  cm	4	-10.6032	5.3431	0.9849	0.2190	0.2194
Trunk 20-30 cm*	58.0 – 161.7 cm	3	-39.1334	16.2632	0.9870	0.4205	0.0253
Sub-Component	Range	u	А	q	$\mathbb{R}^2$	RSD	SSDx
$X = crown area (m^2)$							
Branch <1 cm*	25.5 – 161.7 cm	5	-0.8490	1.9553	0.8724	0.4948	1.3138
Branch 1 – 4 cm*	25.5 – 161.7 cm	5	-0.1625	1.3246	0.4279	1.0135	1.3138
Branch 4-10 cm*	$44.0 - 161.7 \mathrm{~cm}$	4	-2.5287	3.6670	0.9260	0.4850	0.4380
Trunk $20-30 \text{ cm}^*$	58.0 – 161.7 cm	3	-8.4460	7.4339	0.4464	2.7418	0.0549
*Components measurements based o	on diameter						

Allometric equations for the estimation of sub-component biomass of the form  $y = a + b \ln x$  for Eucalyptus melanophloia in

Table 8.5

<sup>&</sup>lt;sup>\*</sup>Components measurements based on diameter.

#### 8.5 Allometric Analysis

An important component of the analysis was to establish how well the biomass of the components (i.e., leaves, branches and trunks) determined for the individuals harvested at Injune compared to the estimates generated using the equations of Burrows et al. (1998). Based on this comparison (Figures 8.1 and 8.2), it was evident that the biomass measured from the harvested E. populnea and E. melanophloia deviated from their respective equations, particularly if their circumference was at the edge or outside of the range specified by the original equation (Cronin et al. 2000). For the relationships between circumference at 30cm (converted to D<sub>30</sub>) and leaf and branch biomass, the trendlines representing E. populnea and E. melanophloia equations are similar. Thus, both E. populnea and E. melanophloia harvested individuals adhere to their respective trendlines. However, trees larger than 40 cm in diameter did not adhere as closely as those less than 40cm. This is not the case for the relationships between diameter and the trunk and total biomass. At approximately 40cm, the E. populnea and E. melanophloia trendlines diverged from each other. The harvested E. populnea followed the trendline for E. melanophloia and the harvested E. melanophloia followed the trendline for E. populnea. Although an unexpected outcome of the research, these discrepancies highlight the difficulty in using allometric equations generated at different locations from where they are applied, particularly at the edge of the range. However, the equations also illustrated that, within the range of biomass harvested by Burrows et al. (1998), the allometrics generated previously provide a reasonable representation of the biomass of these species at Injune. A conclusion of this work was that the equations for the two species were similar and that a generic equation could even be formed. However, as the raw data for the previous studies were unavailable and the number of individuals of E. populnea and E. melanophloia harvested at Injune alone was low, the data was considered insufficient for generating site-specific equations. Further harvesting of these species was not possible due to funding and time constraints and the focus of the harvesting was on generating new equations for C. glaucophylla. Therefore, for E. populnea

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and E. melanophloia the original equations for these species (i.e., those generated by Burrows et al. 1998) were used. However, the estimates of small branch (< 1 cm diameter) biomass generated through harvesting E. melanophloia and E. populnea at Injune were used in subsequent parameterisation of the SAR backscatter model.

#### 8.6 Individual species biomass calculation

Based on the existing and new sets of allometric equations, estimates of total and component biomass were generated for each of the 34 Secondary Sampling Units. For C. glaucophylla, the new equations generated at Injune were used whilst for E. melanophloia and E. populnea, and as indicated above, the equations generated by Burrows et al. (1998) were used. For many species (e.g., Eremophila mitchelli, and Geijera parviflora), equations were available. However, for a number of species, no equations existed and therefore the most appropriate equation was applied based on similarities in structure (e.g., Pine or Eucalypt) and growth form (Table 8.6). For most species, the use of the available allometrics was considered acceptable. However, the only exception was Angophora leiocarpa for which an equation was not available. Furthermore, harvesting of this species was unrealistic given the large size of these individuals. The equation for E. melanophloia was used for this species although it was recognised that larger individuals were generally out of range of the existing equations.

When performing the calculation of biomass for the SSUs, individuals that were outside the size (e.g., diameter) range associated with the different equations were identified (Table 8.7). In all plots, few individuals (including A. leiocarpa) were out of range and, of those that were out of range, most were relatively insignificant in terms of the contribution to the overall biomass (e.g., SWB). Each tree that was out of range was therefore considered separately with the values adjusted to a more realistic value. When calculating the biomass of each

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tree within the SSUs, a bias correction factor was applied in all cases where information was available for calculation.



Figure 8.1 Comparison of a) leaf and b) branch dry biomass (kg) estimated from harvested species at Injune and allometrics derived at Dingo. Injune TAGB *E. populnea* and Injune TABG *E. melanophloia* represent the biomass of the harvested E. populnea and E. melanophloia at Injune respectively. The estimates of biomass generated using the equations of Burrows *et al.* (1998) and the associated trendlines are illustrated as clear circles and solid lines respectively.



Figure 8.2 Comparison of a) trunk and b) above ground dry biomass (kg) estimated from harvested species at Injune and allometrics derived at Dingo. Injune TAGB *E. populnea* and Injune TABG *E. melanophloia* represent the biomass of the *E. populnea* and *E. melanophloia* harvested at Injune respectively. The estimates of biomass generated using the equations of Burrows *et al.* (1998) and the associated trendlines are illustrated as clear circles and solid lines respectively.

Derived Allometric	Species to which equation was
Equation	applied
Eucalyptus populnea	Santalum lanceolatum
	Eucalyptus spp.
	Syzygium cormiflorum'ramiflorus form
	Eucalyptus dolichocarpa
	Eucalyptus microcarpa
	Allocasuarina luehmannii
	Eucalyptus chloroclada
	Eucalyptus populnea
	Lophostemon suaveolens
Eucalyptus	Eucalyptus melanaphloia
melanophloia	Angophora leiocarpa
Callitris glaucophylla	Callitris glaucophylla
	Callitris glaucophylla xC. preissii ssp.
Geijera parviflora	Geijera parviflora
Eremophila mitchelli	Xylomelum cunninghamianum
	Acacia leptostachya
	Casuarina sp.
	Canthium sp.
	Notelaea microcarpa
	Lysicarpus angustifolius
	Eremophila mitchellii
	Acacia excelsa
Casuarina cristata	Casuarina cristata
	Hakea fraseri
Flindersia maculosa	Brachychiton populneusssp. populneus
	Acacia ixiophylla
	Acacia neriifolia
	Acacia harpophylla
	Opuntia tomentosa

Table 8.6Allometrics and species to which applied

			eduatory.
SSU	Number of trees outside range	Observed Range <sup>1</sup>	Allometric Range
$111_{-}12$	4	H=6.0-7.7m	H=0-4.5m
$114_{-}12$	11	H=5.0-7.8m	$H=0-4.5\mathrm{m}$
$144_{-}13$	2	$D_{30}=82.7-97.5cm$	$D_{30}=4.3-68.9cm$
$142\_20$	42	H=4.8-7.3m	H=0-4.5m
$142_{-}2$	18	H=5.0-7.7m	H=0-4.5m
$144_{-}19$	1	$D_{30}=55cm$	$D_{30}=8.1-51.5cm$
	80	H=4.8-12.1m	H=0-4.5m
$148_{-}1$	8	H=5.0-7.2m	H=0-4.5m
	2	$D_{30}=27.1-47.8cm$	${ m D}_{30}{=}1.69{-}25.05{ m cm}$
	1	$D_{30}=70.8cm$	$D_{30}=4.3-68.9cm$
1 10 16	2	$D_{30}=65.7-78.7cm$	$D_{30}=8.1-51.5cm$
140_10	3	H=5.50m	H=0.6-5.2m
	2	$D_{30}=28.3-48.6cm$	${ m D}_{30}{=}1.69{-}25.05{ m cm}$
$148_{-}29$	15	H=6.0m	H=0-4.5m
$23\_15$	9	H=6.5-9.0m	$H=0-4.5\mathrm{m}$
99 16	1	$D_{30}=57cm$	$D_{30}=8.1-51.5cm$
01-07	22	H=4.8-9.4m	H=0-4.5m
00 00	4	$D_{30}=62.4-85.8cm$	$D_{30}=8.1-51.5cm$
07 <sup>-</sup> 07	41	H=5.0-13.10m	$H=0-4.5\mathrm{m}$
10 00	1	$D_{30}=58.0cm$	$D_{30}=8.1-51.5cm$
£3_64	65	H=5.0-12m	H=0-4.5m

Table 8.7 (continued overleaf). Individual trees within each SSUs identified as being outside of the size range specified for existing allometric equations.

condary mpling Units	Number of trees outside range	Observed	Allometric Range
68_29	1	$D_{30}=64.50cm$	$D_{30}=8.1-51.5cm$
06 60	1	$D_{30}=72.60cm$	$D_{30}=8.1-51.5cm$
02_0	1	$D_{30}=33.7cm$	$D_{30}$ =1.69-25.05cm
01 0	1	$D_{30}=7.5$ cm	$D_{30}=8.1-51.5cm$
0_10	24	H=5.3-20.4m	H=0.6-5.2m
01 10	3	$D_{30}=60.1-69.5cm$	$D_{30}=8.1-51.5cm$
01-10	17	H=6.8-10.5m	H=0-4.5m
11	1	$D_{30}=78.6cm$	$D_{30}=2.4-69.0cm$
11_11	4	$D_{30}=78.4-93.5cm$	$D_{30}=8.1-51.5cm$
1 / /	1	$D_{30}=95.9cm$	$D_{30}=8.1-51.5cm$
. <b>1</b> 4_4	11	H=5.0-8.7m	H=0-4.5m
	1	$D_{30}=78.3cm$	$D_{30}=4.3-68.9cm$
00 00	6	$D_{30}=53.0-101.5cm$	$D_{30}=8.1-51.5cm$
07_00	5	H=4.6-8.0m	H=0-4.5m
	2	H=4.8m	H=0-4.5m
	6	H=6.0-9.0m	H=0.6-5.2m
38_21	16	$D_{30}=3.0-8.0cm$	$D_{30}=2.4-69.0cm$
	1	$D_{30}=38.7cm$	$D_{30} = 1.69 - 25.05 cm$
$38_{-16}$	1	H=5.5m	H=0-4.5m

#### 8.7 Estimation of Plot Biomass

Based on the available allometrics, estimates of the total and component (leaf, branch and trunk) biomass were generated for each SSU (Table 8.8). The above ground biomass ranged from 1.7 Mg ha<sup>-1</sup> to 140.4 Mg ha<sup>-1</sup>. Differences in the allocation of biomass to different components were also evident. The proportional allocation of biomass to the trunk and branches varied depending largely upon the relative proportion of C. glaucophylla at different growth stages within the community (Figure 8.3). In particular, plots containing a high proportion of C. glaucophylla had greatest allocation to the trunk. However, 29 of the 34 SSUs had an allocation of biomass to the trunk component equal to or more than 50%, while only 3 of the 34 SSUs have an allocation to the branch component of greater than 50%. This indicates that a greater proportion of biomass was allocated to the trunks regardless of the dominance of the species and inclusion of C. glaucophylla.

A. leiocarpa represented approximately 50% of the dominant species present at Injune. For those SSUs containing large numbers of this species, it was evident that allocations of biomass to the trunk and the branches were similar, ranging from 40-50%. A slightly greater distribution of biomass to the trunk rather than the branches was found for SSUs with a high proportion of E. melanophloia. Those SSUs dominated by E. populnea recorded an allocation to branch biomass of approximately 40 % with 43 - 46 % allocated to the trunks.

The cumulative biomass for the leaf, branch and trunk biomass of each SSU is demonstrated in Figure 8.4. Despite 111\_12 and 111\_18 containing the largest number of C. glaucophylla (i.e., dominant trunk allocation of biomass), they do not have the highest cumulative biomass. 81\_11 and 124\_19 have a higher cumulative biomass which is attributed to the presence of a number of A. leiocarpa in each plot.

		Bi	omass (I	Mg ha-1)	
Secondary Sampling Unit	Branch	Trunk	Leaf	<sup>1</sup> Total Above Ground Biomass	<sup>2</sup> Total Above Ground Biomass
111_18	13.9	91.8	5.4	123.2	111.1
111_12	29.8	90.1	7.1	140.4	127.1
114_12	6.5	17.1	1.8	27.9	25.4
114_4	25.5	60.5	3.9	96.6	89.9
124_19	58.5	76.6	3.4	142.7	138.6
124_6	19.0	53.1	4.2	84.9	76.3
131_18	15.8	17.1	1.2	35.9	34.2
131_27	1.6	1.1	2.4	4.3	5.0
138_16	24.5	32.1	2.9	64.0	59.5
138_21	28.3	42.2	3.0	81.6	73.5
138_28	52.6	56.3	1.8	111.7	110.7
142_2	18.4	20.0	1.9	44.8	40.3
142_13	19.9	23.1	1.5	49.4	44.6
142_18	31.2	32.8	1.9	72.0	65.9
142_20	24.1	24.3	2.2	55.5	50.5
144_13	29.9	52.5	2.7	88.5	85.1
144_19	11.9	31.8	2.2	50.2	45.8
148_16	37.5	45.2	2.9	87.5	85.6
148_1	41.5	24.1	9.0	79.5	74.6
148_21	30.9	26.8	3.0	63.3	60.7
148_29	33.6	35.8	3.0	79.4	72.5
23_15	27.3	42.7	3.7	73.8	73.7
23_16	23.4	29.4	2.0	57.1	54.9
23_20	54.2	45.2	3.9	102.8	103.3
23_24	42.0	43.1	5.2	94.0	90.2
58_24	28.7	28.5	1.8	63.4	58.9
58_29	35.5	43.4	2.9	87.8	81.9
59_27	1.3	1.0	0.8	3.0	3.1
59_28	0.5	0.9	0.3	1.7	1.7
81_16	36.7	52.4	3.5	97.2	92.6
81_11	55.2	90.7	3.0	148.9	148.9
81_8	25.2	53.1	3.8	87.4	82.1
83_12	10.7	19.4	1.7	34.9	31.8
83_20	24.2	44.9	2.6	76.8	71.7

Estimates of component (leaf, branch and trunk) and total biomass for Table 8.8 the SSUs sampled at Injune

<sup>1</sup> Total above-ground biomass, as estimated by the allometric equations
 <sup>2</sup> Total above-ground biomass, as derived from the sum of branch, leaf and trunk biomass









# 8.8 Sapwood Area

A slight variation of the allometric equation is the pipe model, which correlates the cross-sectional area of a stem or branch that is responsible for water transport (i.e., sapwood to foliage mass; Shinozaki et al. 1964a,b). Simple linear regression analysis was used to determine the relationship between sapwood area (cm<sup>2</sup>) and foliage biomass (kg). Using the sapwood cross-sectional area, in order to determine leaf biomass, four regression models were developed (Table 8.9). Relationships between sapwood cross-sectional area at the tree base and leaf biomass were established for E. populnea, E. melanophloia and C. glaucophylla. This relationship was also derived at 130cm for C. glaucophylla. A strong linear relationship exists in both models for C. glaucophylla (Figure 8.5 b and c). A strong log-linear relationship exists for E. populnea, although the sample is very small. A weaker relationship was observed for the five-sampled E. melanophloia (Figure 8.5a). These observations suggest that sapwood cross-sectional area may be useful for providing an estimate of leaf biomass.

Table 8.9 Equations and summary statistics to predict foliage biomass from sapwood cross-sectional area using linear equation Y = ax + b (where Y = Foliage biomass Mg ha<sup>-1</sup>) for species *C. glaucophylla* and *E. melanophloia* and log-linear equation Y = aLn (x) + b (where Y = Foliage biomass Mg ha<sup>-1</sup>) for *E. populnea*.

Species	a	b	X	n	$\mathbb{R}^2$
C. glaucophylla	2.7746	695.67	Sapwood cross-section area (m <sup>2</sup> ) at DBH130cm	12	0.98
C. glaucophylla	2.1978	744.66	Sapwood cross-section area (m <sup>2</sup> ) at base	14	0.98
E. melanophloia	1.2106	2124.5	Sapwood cross-section area (m <sup>2</sup> ) at base	5	0.78
E. populnea	2256.4	-10383	Sapwood cross-section area (m <sup>2</sup> ) at base	3	0.98



Figure 8.5 Relationship between sapwood cross-sectional area and leaf biomass for a) E. melanophloia b) *C. glaucophylla* at base of tree and c) *C. glaucophylla* at 130cm

# 8.9 Summary

The process of biomass estimation involved the input of data from a number of sources, with the two fundamental components being the independent variable and the allometric equation. For species whose allometric equations were derived on site (i.e., C. glaucophylla), the reliability of the biomass estimates was considered to be high as a result of the high correlation between the biomass components and subcomponents and the measured structural variables of the tree.

For E. populnea and E. melanophloia, the comparison between the Injune derived allometrics and those derived at Dingo (existing) revealed that the existing equations provided good estimates of the leaf and branch biomass. However, for trunk and total biomass, estimates deviated above a diameter of 40cm.

There were dominant and understorey species, whose independent variables (i.e., H and D) fell outside the specified allometric range. Although considerable in number, the deviations were only small for the understorey species. However, these were significant for the larger species (i.e., A. leiocarpa).

These biomass estimates are employed subsequently in Chapter 10 in establishing relationships between biomass and LIDAR returns, integrated CASI and lidar data, and also SAR backscatter

# **Chapter 9**

# **Structural Characteristics of Woodlands**

# 9.1 Overview

Based on an analysis of the aerial photography acquired over the 150 Primary Sampling Units (PSUs) and the field data collected from the 34 Secondary Sampling Units (SSUs), this chapter provides an assessment of the species/community composition, biomass and structure of woodlands at Injune. This assessment is important as it provides an insight into the ability to subsequently quantify biomass and structural diversity using AIRSAR data. Differences in the allocation of biomass to different components (e.g., branches, trunks) are also reviewed in the context of structure and relationships between structural components are presented, as these were considered important for subsequent parameterisation of SAR backscatter models and the interpretation of the outputs.

# 9.2 Species/community composition

The composition of the forests and woodland communities occurring within the study site were established by summarising the occurrences of species associations and also individual species for the 4500 SSUs (30 per PSU), as determined through interpretation of the Large Scale Photography (LSP; Jones 2000). Within each LSP acquired over the PSUs, different woodland communities were delineated manually onto acetate overlays by Queensland Department of Natural Resources and Mines (QLDDNRM) staff. Each woodland type was then described in terms of species/community composition and crown cover. These overlays were then scanned along with the LSP prior to registration within the Bureau of Rural Sciences (BRS).

As indicated in Chapter 8, the LSP were registered initially using the known locations of the principal points and camera parameters. Comparisons with the lidar data and other datasets confirmed that products from these data were generally accurate to +/-20 m without additional registration. For this reason, further ground control points (GCPs) were taken, using the lidar data as reference, which resulted in root mean square (r.m.s.) errors of < 2 m. Polygon line work relating to the distribution of woodland types and captured within each LSP was also scanned, vectorized and rectified using the same transformation as the digital LSP, thereby facilitating direct comparison between LSP and lidar data (and derived products). On this basis, each of the 4500 Secondary Sampling Units was associated with a woodland community type together with an assessment of the dominant, co-dominant and subdominant or understorey species.

In a number of tables and figures through this chapter, acronyms are used to represent species and species associations. It was impossible to use entire species names and associations containing species names in these tables and figures due to space restrictions, so a table is provided in Appendix A, which explain the codes.

#### 9.2.1 Dominants, co-dominants and understorey species

Within the 4500 SSUs at Injune, ~70 % of the dominant species were represented by C. glaucophylla, E. melanophloia, A. leiocarpa and Eucalypt.spp, with C. glaucophylla being the most common (Figure 9.1a). Only 10 % of the Injune study site was non-forest (i.e., areas that have no vegetation cover). Within the remaining 20 %, other species dominated including E. decorticans, E. dealbata and E. fibrosa ssp. Fibrosa (Figure 9.1b and c).

Of the co-dominant species present at Injune, E. melanophloia, Eucalypt.spp, C. glaucophylla and A. leiocarpa accounted for 66% (Figure 9.2a). The remaining codominants represented 20% and featured predominately Eucalyptus species, such as E. decorticans, E. dealbata and E. populnea (Figure 9.2b and c).

Subdominant or understorey species were absent from 35 % of the PSUs. Where subdominants or understorey did occur, it was dominated by Eucalyptus species (particularly E. melanophloia), C. glaucophylla and A. leiocarpa dominated (Figure 9.3 a), although a diversity of other species was present (Figure 9.3 c and b). Such species, many of which are more commonly recognised as being understorey species, included Acacia species and E. mitchelli.

Species associations were commonplace. C. glaucophylla - E. melanophloia formed the most extensive association. Other common species associations include C. glaucophylla, A. leiocarpa, A. leiocarpa- C. glaucophylla and E. melanophloia- C. glaucophylla. However, these associations as well as the non-forest component represented only 31% of all associations. The remaining 69% were dominated by other associations including E. melanophloia-Eucalypt.spp and C. glaucophylla -Eucalypt.spp (Figure 9.4b and c). Overall, the Injune study-site encompassed a wide variety of species associations, dominated by Eucalyptus, Callitris and Angophora species. Of the woodland communities identified at Injune, 45.5 % were sampled (in terms of species composition and dominance) by the 34 SSUs (Table 9.1). The Primary Photo Plots (PPPs) covered an area greater than the PSUs (i.e., 64 ha), and the 34 Secondary Sampling Units sampled 44.5 % of these communities. Most of the main communities were sampled by the SSUs (e.g., C. glaucophylla - E. melanophloia - Eucalypt.spp which represented 10.8 % of the woodland communities sampled by the 4500 SSUs). The remaining proportion of the woodlands generally contained a diverse mix of species, with most of these communities individually representing < 1 % of the total. This observation reflects the enormous diversity of species associations that occur at Injune. However, the number of species is not large, just that these occur in differing combinations, as dominants, co-dominants and subdominants/understorey. Taking into account the vegetation clearance regime occurring over the past ten years, in particular, it is understandable that the 'Non Forest' component was present in a significant proportion (10.1 %) of SSUs.









I able 9.1		r ov er.	הם מו זוון הבילוביים	me by m		os, ordereu oli ulle oc ppp	pasts of frequencies	tericy or occu		SUSC V	
composition (	equivalent of 40 differed slightly	. See Apl	vooulallu pendix A	for specie	es codes.	le FFFS COVEIEU A	greater area u			no ann an	hununu
Type	SSU	No. of	% of	No. of	% of	Type	SSU	No. of	% of	No. of	% of
1	Sampled in	SSUs	total	PPPs	total	1	Sampled in	SSUs in	total	PPPs	total
	the field	in	SSUs	in	PPPs		the field	study area	SSUs	in	PPPs
		study area		study area						study area	
<b>CP-SLIEUS</b>	$124_{-6}$	484	10.8	1087	11.34	CP-ECHSLI	$144_{-}19, 144_{-}13_{-}5$	24	0.5	6	0.01
Non-forest	$59_27, 59_28, 1$ $31_27$	455	10.1	869	9.05	SLISBACP-	$138_{-}16, 138_{-}28$	22	0.5	16	0.16
CP-SBA-EUS	$114_{-}12, 114_{-}4$	204	4.5	358	3.73	EUSCP-SBA	$124_{-}19$	16	0.4	24	0.25
CP-EUS	81_8, 83_20	156	3.5	355	3.7	PBXEUSWAT	$142_{-}2, 142_{-}13$	14	0.3	13	0.14
CP-SLI	83_11	148	3.3	579	6.03	PBXEUSWATPB XCP-EUS	148_21	14	0.3	16	0.17
CP-SLI-SBA	$111_{-}12, 111_{-}18$	139	3.1	273	2.8	<b>CP-WATEUS</b>	81_11	11	0.2	10	0.1
SLICP-	$81\_16, 138\_21$	66	2.2	252	2.6	SLIPBXSWB	$58_{-}29$	œ	0.2	4	0.04
SLI-CP-EUS	$23\_15$	71	1.6	166	1.7	RBA	$23_{-}24$	8	0.2	10	0.1
SBAEUSCP-	$23_{-}16, \ 23_{-}20$	47	1	06	0.9	SLISWB	$131_{-}18$	J.	0.1	4	0.04
PBXEUS	$148_{-}29$	68	1.5	80	0.83						
PBXSWBSLI	$148_{-}16$	25	0.6	20	0.2	BGLSWB	$148_1$	2	0.0	2	0.02
PBXSWB	$58_24,142_18$ $142_20$	25	9.0	43	0.45						
							% of Total	45.5		44.5	

Woodland types sampled at Injune by the 34 SSIIs ordered on the basis of frequency of occurrence by SSIIs The SSIIs Table 9.1

## 9.3 Distribution of biomass

## 9.3.1 Estimating biomass using lidar

To provide an estimate of the biomass for each of the 4500 PSUs, relationships were generated between total above ground biomass and the Lidar data. This relationship and subsequent estimates of biomass across the PSUs used in this study were made available by the BRS (Tickle et al. 2003). The process involved a) slicing the Lidar data into 5 m intervals and extracting the number of Lidar strikes per interval (indicative of the vertical distribution of scattering elements). When developing the algorithm, the selection of the 5 m interval was considered appropriate as significant structural variability (up to 35 m) was considered and the number of explanatory variables was not too large; b) for each of the 34 SSUs, establishing a step-wise linear regression between the biomass for each SSUs and the proportion of Lidar returns within each height interval class (Equation 9.1; Table 9.2); and c) applying the resulting regression to the remaining Secondary SSUs, thereby generating 4,500 estimates of total above ground biomass.

The step-wise regression equation generated is given below:

$$Y = \beta_1 \chi_1 + \beta_2 \chi_2 + \dots + \beta_6 \chi_6 + \Sigma$$
 Equation 9.1

where Y represents above ground biomass (Mg ha<sup>-1</sup>) and  $\chi_n$  and  $\beta_n$ , the proportion of Lidar vegetation hits for given height classes and the corresponding regression coefficients respectively (Table 9.2).

Table 9.2 Height classes for  $\chi_n$  variables (proportion of lidar vegetation hits within height class (m)) and the regression coefficients ( $\beta_n$ ) for each height class

Variable	Height class (m; $\chi$ ) within which the	<b>Regression coefficient</b>
number	proportion of lidar vegetation hits	for height class (β)
	was determined.	
1	0.5-5.0	0.168
2	5.0-10.0	1.947
3	10.0-15.0	0.857
4	15.0-20.0	3.589
5	20.0-25.0	19.910
6	25.0-35.0	20.00





The lidar predictions of biomass generated a strong linear relationship with an adjusted  $r^2$  of 0.89 and SE of 11.01 Mg ha<sup>-1</sup>. As the ground estimates of biomass were not free of error, the Lidar predictions were plotted back over the field estimates, revealing that 69 % fell within the 95 % confidence limits of the data. A t-test of the two estimates also revealed no significant difference (P < 0.05) between the Lidar and field-based predictions of biomass (Tickle et al. 2003).

#### 9.3.2 Distribution of biomass at Injune

Based on the analysis of biomass estimated using the PSUs, an understanding of the distribution of biomass was provided. Approximately 46.5 % of woodlands contained within the SSUs supported an above ground biomass greater than the mean of 86 Mg ha<sup>-1</sup> (Figure 9.6).

A summary of the distribution of biomass at Injune is provided in Table 9.4. At Injune, over 59.7 % of the woodlands support a biomass of < 100 Mg ha<sup>-1</sup> which is below the saturation level observed, in a number of studies, by L-band and certainly P-band. However, 43.9 % of the woodlands support a biomass of between 50 and 100 Mg ha<sup>-1</sup> which is above the reported saturation level for C-band with a small proportion supporting a biomass greater than 150 Mg ha<sup>-1</sup>. A further 32.3 % support a biomass above 100 Mg ha<sup>-1</sup>. Only 9.9 % of woodlands support a biomass of < 20 Mg ha<sup>-1</sup>, which includes non-forest areas.

For different levels of biomass, the composition of the species is noticeably different (Table 9.4). For forests up to 10 Mg ha<sup>-1</sup>, A. harpophylla is common. However, within the 10-50 Mg ha<sup>-1</sup>, there exist numerous associations of Callitris and Eucalyptus species, dominated by associations of C. glaucophylla and E. melanophloia. For the biomass ranging from 50-100 Mg ha<sup>-1</sup>, a similar trend is evident in which there are many associations of Callitris and Eucalyptus, with associations of C. glaucophylla - E. melanophloia, C. glaucophylla –A. leiocarpa and C. glaucophylla - E. dealbata dominating. For biomass exceeding 150 Mg ha<sup>-1</sup>, the prevalence of associations involving Angophora species becomes more apparent.



Figure 9.6 Frequency histogram of above ground biomass (mean = 86 Mg ha<sup>-1</sup>, median = 83 Mg ha<sup>-1</sup>) estimated using a relationship established with lidar data.

Table 9.3	Percentage and cumulative percentage distribution of biomass, within
	the 4500 SSUs

Biomass Range (Mg ha <sup>-1</sup> )	Percentage	Cumulative Percentage
< 10	8.2	8.2
10-20	1.7	9.9
20-50	5.9	15.8
50-100	43.9	59.7
100 – 150	32.3	92.0
> 150	8.0	100

Table 9.4Distribution of above ground biomass (as estimated using LIDAR data) by common woodland types (based on presence<br/>of dominant and co\_dominant species within SSUs). Note that only types where > 2  $\%^*$  of the biomass is contained are listed and the values refer to the numbers of SSUs. See Appendix A for species codes.

Up to 10		>10 5	0	>50-100	_	>100-15	0	>150		All fore	sts
Mg ha <sup>-1</sup>		Mg ha <sup>-</sup>	-1	Mg ha <sup>-1</sup>		Mg ha <sup>-</sup>	1	Mg ha <sup>-1</sup>			
Others	<b>*</b> 4	Others	*30	Others	*39	Others	*26	Others *2	28	Others	*36
Non For.	84	Non For.	11	<b>CP-SLI</b>	20	CP-TDG	30	SBACP-	24	<b>CP-SLI</b>	18
BGL	×	<b>CP-SLI</b>	6	<b>CP-SBA</b>	12	<b>CP-SLI</b>	14	CP-SBA	16	<b>CP-SBA</b>	10
SWBWAT	2	SLICP-	9	SLICP-	7	<b>SBAEUS</b>	8	SBAEUS	12	Non For.	10
<b>CP-SLI</b>	2	SLIEUS	9	SLIEUS	9	<b>CP-PBX</b>	5	GTIEUS	4	SBACP-	9
		PBXEUS	5	<b>CP-EUS</b>	5	SLIEUS	4	<b>CP-SLI</b>	3	SLICP-	5
		BLINRI	4	SBACP-	4	EUSSBA	2	<b>CP-EUS</b>	S	SLIEUS	4
		CP-TDG	4	PBXEUS	3	SLIGTI	2	SBA	ŝ	<b>CP-EUS</b>	4
		SBAEUS	4	EUSCP-	3	BRISLI	2	NRITDG	3	SBAEUS	2
		<b>CP-SBA</b>	3	PBX	3	SBANRI	2	BRIGTI	2	PBXEUS	2
		<b>CP-EUS</b>	2	PBXSWB	2	GTINRI	2	RBAECH	2	PBX	5
		<b>CP-RBA</b>	2	<b>CP-RBA</b>	2	BRIGTI	2	TDGCP-	2		
		SBACP-	2	BRIGTI	2	GTICP-	2	BRIEUS	2		
		PBXSWB	2					EUSCP-	2		
		RBASLI	2					SBATDG	2		
		EUSWAT	2					SLICP-	2		
		PBXECH	2								
		WATSLI	2								

#### 9.4 Assessment of structure based on allocation of biomass

The structure of woodlands, and particularly differences in the vertical and horizontal distribution of tree components (e.g., branches, trunks); will influence the attenuation of microwaves, their interaction (i.e., scattering mechanisms) and the magnitude of their return to the SAR.

Depending upon the form and growth of the tree, the allocation of biomass to different components (i.e., leaves, branches and trunks) varies (referred to as ontogenic drift). In the following sections, the allocation of biomass to different components is outlined for species based on available allometric equations, sampling and harvesting information.

Using this information also, the dry weight percentage allocation to the different components by species (e.g., C. glaucophylla, E. populnea and E. melanophloia) is outlined in more detail. For analysis and illustrative purposes also, dry weight percentages of the major above ground sub-components (e.g., leaves, branches, trunks, branches < 1 cm, 1- 4 cm, 4-10 cm and > 10 cm) were calculated for each of the harvested trees and used to establish trends in allocation. In the following sections, excurrent and decurrent forms are considered in turn.

### 9.4.1 Decurrent growth forms

Tree species with a decurrent growth form included species of Eucalyptus, Angophora and Acacia and also those occurring in the understorey.

#### 9.4.1.1 Eucalyptus species

E. populnea and E. melanophloia were considered representative of many of the Eucalyptus species occurring within the Injune study area. For these two species, allometric equations already existed and harvesting of both had occurred at Injune to provide a better indication of the allocation of biomass.

Furthermore, a parallel study aimed at assessing the utility of randomised branch sampling (RBS) and importance sampling (IS) for estimating the biomass of E. populnea was undertaken at Dingo in central Queensland (Good 2001). These data were combined to provide an insight into the allocation of biomass to different components.

Using the equations of Burrows et al. (1998), it was evident that at diameters (measured at 30cm;  $D_{30}$ ) up to 30-40 cm, E. populnea allocated more than 50 % of the biomass to the branches (Figure 9.7). For trees of larger diameter, the allocation to the trunk increased but did not exceed 60 % of the total and the proportion of biomass allocated to the leaves decreased.

The result of applying the equations beyond their intended range is also illustrated. The range for each of the equations is represented by the blue lines on Figures 9.7a, 9.8 and 9.10a. This range is significant, as it is a limitation on the diameter of the trees for which the biomass can be accurately derived.

Based on 10 E. populnea trees harvested at Dingo (Figure 9.8a) and 7 harvested at Injune (Figure 9.8b), a trend in the allocation of biomass to the branch (including subcomponents) is not so evident. Even so, trees at both Dingo and Injune allocated only a very small proportion of their biomass to the small (< 4 cm branches) and leaves and there is a general decrease in the proportion of leaf biomass as the diameter increases. At Dingo also, some E. populnea supported dead components which represented a significant proportion of the total standing biomass (live + dead). Two conclusions can be drawn from these results. First, there is enormous variability in the allocation of biomass to branches and trunks by E. populnea which cannot always be captured using allometric equations. The diversity of branch and trunk sizes and orientations observed within woodlands dominated by E. populnea supports this conclusion. Second, the biomass of trees of similar diameter harvested at Dingo and Injune differed substantially, which can be attributed partly to the different climatic conditions (Dingo is generally less arid). The importance of generating sitespecific allometric equations is therefore highlighted.

Based on the equations of Burrows et al. (1998), a smaller proportion (less than 40-50 %) of the biomass of E. melanophloia was allocated to the branches (Figure 9.9), with this proportion increasing only slightly with increases in diameter (for trees > 20 cm in diameter,  $D_{30}$ ). For trees < 20 cm diameter, a lower (less than 30 %) proportion of biomass was allocated to the trunks. Leaf biomass represented approximately 15% of the total biomass for the diameters up to 10cm but decreased with the subsequent increases in diameter. Of the five E. melanophloia trees harvested at Injune, leaf biomass was shown to decrease in proportion to diameter whilst the allocation to the trunk increased. Harvesting of an individual E. melanophloia at Dingo indicated that the greatest allocation of biomass was to the trunk.

## 9.4.1.2 Angophora species

Allometric equations relating tree size to the total above ground and component biomass of A. leiocarpa were not available. However, based on RBS and IS at Injune (Good 2001), estimates of the component biomass (including sub-components) of four large (> 30 cm diameter) A. leiocarpa were generated. This analysis confirmed that a large but variable proportion of biomass was allocated to the branches and trunks. The variation was expected and attributed to the differing environmental and growth conditions associated with the individuals harvested.

#### 9.4.1.3 Acacia species

Of the Acacia species occurring at Injune, equations were only available for A. harpophylla (Scanlan 1991) although on-site harvesting of a large individual A. harpophylla was undertaken.



The proportion of biomass allocated to leaf, branch and trunk components for E. populnea trees of varying diameter, as estimated using allometric equations of Burrows et al. (1998). The blue lines indicate the diameter range (4.3 - 68.9cm at 30cm) of the trees harvested in order to derive these equations. Figure 9.7
The proportion of biomass allocated to leaf, branch (< 1 cm, 1-4 cm, > 4 cm) and trunk components for E. populnea based a) on actual trees harvested at Dingo and b) actual trees harvested at Injune. Figure 9.8





a)

q

The sampled diameter range of 5 - 30cm (D<sub>30</sub>) had a corresponding height range of 1-4m, which was inside the specified range for the equations of Scanlan (1991). The equations suggested that, within this size class, approximately 60% of the biomass is allocated to the leaves (Figure 9.10a). The foliage of A. harpophylla is distinctly hard and thick, which may explain the unusually large allocation. The trunks are allocated the smallest proportion, while the branches account for approximately 30%.

## 9.4.1.4 Understorey species

Equations for several species occurring in the understorey were also available, although these typically did not separate branch and trunk biomass. G. parviflora was not as common at Injune as at Talwood (Cronin et al. 2000). This species allocates a large proportion of the biomass (~ 40 %) to the branch component in the early stages of growth although this proportion declines (to < 25 %) with increases in diameter (Figure 9.10b). G. parviflora has a distinct weeping habit and leafy appearance and is typically single stemmed. The sampled diameter range of 5-30 cm and the corresponding height range of 1 - 4m were generally inside the specified range for the application.

Equations were also available for E. mitchelli (Harrington 1979). As with G. parviflora, the proportion of biomass allocated to the leaves, decreased with increases in diameter, from approximately 32 % to < 20 % (Figure 9.10 c). At Injune, Good (2001) applied RBS and IS techniques to estimate the biomass of an SWB individual, of 21.4cm in diameter. The largest allocation of biomass was to the branches > 4 cm sub-component (~ 45% of the total), while approximately 25% of the biomass was allocated to the trunk. The remaining biomass was allocated to 1 - 4cm branches (~ 16% of total) and the leaf and < 1cm branches (~ 5% of total).



Figure 9.9 The proportion of biomass allocated to leaf, branch and trunk components for E. melanophloia trees of varying diameter, as estimated using allometric equations of Burrows et al. (1998). The blue lines indicate the diameter range (8.1-51.5cm) of the trees harvested in order to derive these equations.



Figure 9.10 The proportion of biomass allocated to leaf, branch and trunk for a) *A. harpophylla* based on equations of Scanlan (1991) and leaf and wood components for the species b) *G. parviflora and* c) *E. mitchelli* based on equations of Harrington (1979).

a)

b)

c)

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## 9.4.2 Excurrent growth form

The tree species at Injune that exhibited the excurrent growth form included C. glaucophylla and the Family Pine, which is a combination of C. glaucophylla x C. preissii ssp. Verrucosa. Estimates of the biomass of subcomponents for trees of varying diameter were obtained using the C. glaucophylla allometric equations. These equations indicated that the majority of the biomass was allocated to the trunks with the proportion increasing with diameter (Figure 9.11). Only during the early growth stages of growth, was a larger proportion of biomass allocated to the leaves and branches.

The biomass data for the individual components of the harvested C. glaucophylla (Figure 9.12) revealed that branches of 1-4 cm diameter only occurred on trees >  $\sim$  6 cm diameter whilst branches of 4-10 cm started to occur on trees >  $\sim$  20 cm diameter at 30cm (D<sub>30</sub>). No branches > 10 cm diameter was observed. Furthermore, the proportion of leaf and small (< 1 cm) branch biomass showed only a slight decrease over time suggesting a proportional increase in leaf biomass with overall biomass. One individual tree of the Family Pine species was also harvested at Injune using IS and RBS techniques (Good 2001). This individual had allocated greater than 60 % of the biomass to the trunk and  $\sim$  15 % each to the branches (all subcomponents) and leaves. The remaining biomass was allocated to the dead (> 4 cm) branch subcomponent.



The proportion of biomass allocated to leaf, branch and trunk components for C. glaucophylla trees of varying diameter as estimated using allometric equations generated at Injune. The blue lines indicate the diameter range (2.4-69cm) of the trees harvested in order to derive these equations. Figure 9.11





## 9.5 Structural relationships

Relationships between structural parameters were also considered important, particularly for the parameterisation of the SAR backscatter model (Chapter 12). These relationships also provided an insight into the overall structure and development of the forests and woodlands at Injune. Furthermore, by establishing relationships with attributes that are used as independent variables in allometric equations (e.g., Burrows et al. 1998), options for quantifying biomass using a wider range of data (e.g., crown area) are provided.

Relationships between the structural attributes listed in Table 9.5 were considered for the main dominant species occurring within the Injune study area, namely C. glaucophylla, E. populnea, E. melanophloia and A. leiocarpa. Relationships were established based on harvested species but also individually for each SSU and by growth stage. The results from specific SSUs are provided below.

	DBH	$CD_{FLB}$	CD <sub>CB</sub>	CA
Н				
DBH				

The canopy dimensions estimated from the field data included canopy depth to canopy base ( $CD_{CB}$ ) and first leafing branch ( $CD_{FLB}$ ) and the crown area (CA), with the latter calculated from the dimensions of the crown in the east-west and north-south directions and using the formula for both a circle (based on average of the two radius measurements) and ellipse (based on the lengths of the semi-major and semi-minor axes). For Eucalyptus species, trunk height was generally estimated as the height to the first leafing branch.

Table 9.5Structural attributes between which relationships were established,<br/>where H represents crown top height (m), DBH represents diameter at 130 cm,  $CD_{CB}$ <br/>and  $CD_{FLB}$  represent crown depth to the crown base and first leafing branch<br/>respectively and CA represents crown area.

## 9.5.1 Relationships between diameter and height

Based on the harvested species at Injune, a strong non-linear relationship was observed between DBH and H for all species (Figure 9.13). For E. populnea, the maximum height of 16 m was attained at a diameter of ~ 35 cm ( $R^2 = 0.64$ , n = 7) suggesting that above a certain DBH, height increases were minimal. In contrast, H increased steadily with DBH for both E. melanophloia ( $R^2 = 0.91$ , n = 5) and more so for C. glaucophylla ( $R^2 = 0.9$ , n = 20).

When individual SSUs were considered (Figure 9.14), similar patterns were observed. For E. populnea, an asymptotic increase in H to about 16-18 m at a DBH of about 22-23 cm was observed ( $R^2 = 0.69$ , n = 202). For E. melanophloia, H increased with DBH ( $R^2 = 0.70$ , n = 407) but tended towards an asymptote of ~ 18-20 m and some scatter was observed, although less compared to E. populnea. For C. glaucophylla, H increased with DBH ( $R^2 = 0.91$ ), following a more linear trend. However, a strong log relationship was also observed for C. glaucophylla (Figure 9.14c), whereby the increase in height tended towards an asymptote of ~ 23 m. The H of A. leiocarpa also increased with DBH ( $R^2 = 0.84$ , n = 103), tending towards an asymptote at approximately 25 – 35 m.



y = 6.2312Ln(x) - 7.8114

 $R^{2} = 0.9127$ 





Diameter at 30cm (cm)

с С





a)

## 9.5.2 Relationship between height, diameter and crown depth

The region of the vertical profile represented by both  $CD_{FLB}$  and  $CD_{CB}$  includes branches and leaves. However, the area between  $CD_{FLB}$  and  $CD_{CB}$  often includes only branches. Relationships were therefore established between H and both  $CD_{FLB}$  and  $CD_{CB}$  to examine how leaves and branches are distributed.

## 9.5.2.1 Height Relationships

Using field measurements from the SSUs, power or log-linear relationships between CD<sub>FLB</sub> and H were observed for decurrent species (Figure 9.15). For E. populnea, the H-  $CD_{FLB}$  relationship ( $R^2 = 0.66$ , n=201) indicated that, in the early stages, approximately 50 % of the vertical profile was occupied by the crown which increased to ~ 66 % in larger trees. For E. melanophloia, the relationship  $(R^2 = 0.50, n=429)$  suggested that approximately 50 % of the vertical profile was occupied by the crown, regardless of size. For C. glaucophylla ( $R^2 = 0.88$ , n=687), the crown depth increased with H with between ~50 and 66 % of the profile representing the crown. For A. leiocarpa ( $R^2 = 0.80$ , n=140), just over 50 % of the profile was occupied by the crown, with a slight increase in crown depth observed. These relationships therefore reflect the different growth patterns between the decurrent and excurrent forms. Similar relationships were also observed between CD<sub>CB</sub> and H, although a more linear relationship was observed. For E. populnea (Figure 9.15a), in particular, CD<sub>CB</sub> was approximately 50 % of the total H, suggesting that the difference between  $CD_{CB}$  and  $CD_{FLB}$ (CD<sub>FLB</sub>-CD<sub>CB</sub>, i.e., the area with few leaves) is in a vertical region of a depth approximating 15-16 % of the total H when approaching maturity. Furthermore, CD<sub>FLB</sub>-CD<sub>CB</sub> increases with H. For E. melanophloia (Figure 9.15b), the CD<sub>CB</sub> increased linearly (slope of 0.43) with H but at a lower rate compared to CD<sub>FLB</sub> (slope of 0.53) indicating an increase in CD<sub>FLB</sub>-CD<sub>CB</sub> with H. With C. glaucophylla, the CD<sub>FLB</sub>-CD<sub>CB</sub> increased with size but not to the same extent as E. populnea and E. melanophloia. The largest increases in CD<sub>FLB</sub>-CD<sub>CB</sub> were observed for A. leiocarpa.

## 9.5.2.2 Diameter Relationships

Relationships between  $D_{130}$  and  $CD_{FLB}$  and  $CD_{CB}$  were also considered (Figure 9.16). These relationships were generally poorer than those obtained with H, with greater scatter, although an overall increase in both crown attributes with  $D_{130}$  was observed. Relationships were generally stronger when  $CD_{FLB}$  was regressed against diameter.

According to the field data, obtained from the Secondary Sampling Units, the relationships between  $D_{130}$  and  $CD_{FLB}$  and  $CD_{CB}$  for C. glaucophylla and A. leiocarpa were described by linear and polynomial functions respectively. These relationships were of a similar magnitude (C. glaucophylla:  $CD_{FLB} R^2=0.79$ ,  $CD_{CB} R^2=0.74$ , n=687 A. leiocarpa:  $CD_{FLB} R^2=0.74$ ,  $CD_{CB} R^2=0.64$ , n=140) and were stronger than those for the eucalypt species. No defined relationship was evident for E. populnea for both variables of crown depth.

#### 9.5.3 Relationship between height, diameter and crown area

Based on measurements of the harvested species individuals at Injune, a strong non-linear (exponential) relationship was observed between  $D_{30}$  and H and crown area for all species.

Strong relationships between crown area and  $D_{30}$  were also observed for the harvested individuals (Figure 9.17). For E. populnea, an exponential increase in CA with diameter was evident ( $R^2 = 0.75$ , n = 7). For E. melanophloia, the increase was generally linear ( $R^2 = 0.97$ , n = 5). For C. glaucophylla, an exponential increase ( $R^2 = 0.92$ , n = 22) was also observed which tended to increase at a greater rate at about 40-45 cm diameter and a CA of 4.5 m<sup>2</sup>.

For E. populnea (Figure 9.18) a very gradual increase in CA with H ( $R^2 = 0.97$ , n = 7) was observed for smaller sized individuals. However, once, the maximum height of ~ 18 m had been attained, large variations in CA became evident and crowns as large as 10 m<sup>2</sup> were formed. For E. melanophloia, a steady increase in

CA with H was observed ( $R^2 = 0.96$ , n = 5), although crowns were generally smaller and a narrower range of areas was observed at the maximum height of ~ 16 m (based on harvested individuals). For C. glaucophylla, an increase was also observed to an asymptote ( $R^2 = 0.77$ ) and crowns were of similar size to those of E. melanophloia, with a similar variation in area observed at the maximum height of ~ 22 m.

Based on the field data obtained for the SSUs, similar relationships were also observed between height and crown area (Figures 9.19) and diameter and crown area (Figure 9.20). The strongest relationships were between CA and  $D_{130}$ , where E. populnea (R<sup>2</sup>=0.43, n=201) and A. leiocarpa (R<sup>2</sup>=0.61, n=146) demonstrated an exponential increase in CA with  $D_{130}$ . For both C. glaucophylla (R<sup>2</sup>=0.80, n=687) and E. melanophloia (R<sup>2</sup>=0.78, n=429), the increase was represented by the power function.

The relationship between height and crown area was most appropriately described by an exponential function for E. populnea, E. melanophloia and A. leiocarpa, whereby an increase in H paralleled an asymptotic increase in CA. A. leiocarpa exhibited the strongest relationship between H and CA ( $R^2=0.70$ , n=140). C. glaucophylla demonstrated a more gradual increase in CA with height, with this relationship represented by a power function ( $R^2=0.58$ , n=687). The narrow crown of this species, in relation to the crowns of the decurrent species is testimony to this.

Two important conclusions can be drawn from this study. Firstly, the crown area increases, particularly when the trees have attained their maximum height and for decurrent species, which indicates a strategy of crown expansion once a certain height has been reached. Second, this increase in crown area is in proportion to the increase in  $D_{30}$  and/or DBH and is therefore reflective of increases in biomass.



С С



q

a)





С С





ට

 $\bigcirc$ 

Diameter at 30cm (cm)







Figure 9.18 Relationship between height and crown area for a) **E. populnea** b) **E. melanophloia** and c) **C. glaucophylla** harvested at Injune



Relationships between H and CA for a) E. populnea (based on data from PSU 142), b) E. melanophloia (based on data from several PSUs), c) C. glaucophylla (based on data from PSU 111) and d) A. leiocarpa (based on data from several PSUs). Figure 9.19





## 9.6 Summary

The analysis of the structural and biomass data for Injune has provided a unique insight into the dynamics of the woodlands and an understanding of the growth strategies adopted by the different species.

In terms of overall species composition, C. glaucophylla, E. melanophloia, E. populnea and A. leiocarpa dominate the majority of woodlands. The diversity of woodlands, both in terms of species and structures, is attributed to the inclusion of these species and a diversity of less common species in varying proportions and as either co-dominants, subdominants or understorey species. Both decurrent (mainly Eucalyptus, Angophora and Acacia species) and excurrent forms (Callitris species) occur in the woodlands, with the former allocating a greater proportion of the biomass to the trunks. Regrowth and understorey species (e.g., A. harpophylla, E. mitchelli and G. parviflora) have a significant proportion of the biomass allocated to the leaves and branches.

The biomass of these woodlands generally does not exceed 150 Mg ha<sup>-1</sup>, although stands of A. leiocarpa contribute a higher biomass (exceeding 150 Mg ha<sup>-1</sup>). Low biomass woodlands are scarce because of the dominance of clearing in the area, although extensive tracts of Brigalow regrowth/scrub occur. Most woodland is in the biomass range 50-100 Mg ha<sup>-1</sup>, which is below the saturation range of most SAR frequencies. However, a significant proportion exceeds 100 Mg ha<sup>-1</sup> and it is likely that their biomass may only be retrieved using lower frequency (e.g., P-band SAR).

Strong relationships exist between a range of structural attributes, namely DBH, H,  $CD_{FLB}$ ,  $CD_{CB}$  and CA. Of interest is that the relationship between DBH and H reaches an asymptote for most species (i.e., at the maximum height), although is variable between species. However, as this asymptote is reached, the CA increases with DBH for all species. This observation suggests that estimates of H could be used to estimate biomass in the early stages of growth

but then CA could then be used subsequently. However, the relationships will depend upon the stocking of species within the woodlands. Such relationships are particularly evident in open woodlands and will decrease in strength with crown closure and density. As Foliage Projected Cover (FPC) is a measure of structure (obtained from the Landsat ETM+ SWIR channels) and crown cover (obtained largely through the relationship with NDVI), such a measure can be expected to be an important indicator of biomass.

In the next chapter, the variability observed in species, structure and biomass within the SSUs will be investigated in terms of it's impact on the empirical relationships between SAR backscatter and both biomass and FPC.

# Chapter 10

# **Empirical Relationships**

# 10.1 Overview

This chapter explores empirical relationships between above ground and component biomass and SAR backscatter at different wavelengths and polarisations, as these have been used in many previous studies for spatially estimating biomass. The influence of incidence angle and woodland structure on these relationships is considered. Within Queensland, FPC derived from Landsat sensor data is commonly used as a surrogate for woodland basal area, which itself relates to biomass. For this reason, relationships between FPC and SAR backscatter are also formulated and discussed.

10.2 Relationships between component biomass and SAR backscatter Initially, relationships were established between the estimates of biomass generated for each of the 34 SSUs and the SAR backscatter (non CTIC) from the 50 x 50 equivalent areas. These relationships (based on the log of biomass) are illustrated in Figures 10.1 to 10.4. In all cases, increases in SAR backscatter at all frequencies and polarisations with leaf + small branch, branch and trunk biomass (as well as the total) were observed. R<sup>2</sup> values for these relationships were strongest in the relationship with L-band and P-band HV backscatter and the biomass of all components but were relatively weak for the other frequencies. The similarity in the relationships confirms that there are inherent relationships between the different biomass components, which complicate our understanding of the SAR response. The results do, however, indicate that HV polarisations are perhaps well suited to estimating the total biomass of these woodlands and even inferring the component biomass. However, the inherency of these relationships suggests that the simulation of the SAR return using forward scattering models might provide a better understanding of microwave interaction. This approach is addressed in Chapter 12.



Figure 10.1 Empirical relationships between SAR backscatter and total biomass



Figure 10.2 Empirical relationships between SAR backscatter and trunk biomass



Figure 10.3 Empirical relationships between SAR backscatter and branch biomass



Figure 10.4 Empirical relationships between SAR backscatter and leaf + small branch biomass

10.3 Community composition, biomass and AIRSAR data.

For each SSU, the composition of the woodland community had been determined through API. Estimates of above ground biomass had also been generated for each SSU using the relationships established with lidar data. Therefore, to establish relationships with lidar-derived biomass by community, AIRSAR backscatter data (all frequencies and polarizations) were extracted from the 4500 SSUs contained within the area of the four flight lines. For some PSUs (e.g., 1, 2 and 3), AIRSAR data were not acquired and hence these data were excluded from the analysis.

Prior to extraction, the C-, L- and P-band AIRSAR data were synthesised from the multilook (16-look) compressed Stokes Matrix into HH, VV and HV polarisations (as well as total power, TP) and in units of intensity (van Zyl et al. 1987, Zebker et al. 1987). The intensity data were converted subsequently to backscattering coefficient ( $\sigma^{\circ}$ , m<sup>2</sup>m<sup>-2</sup>), defined as the average radar cross-section per unit area of the individual scattering elements (Equation 10.1).

$$\sigma^{\circ}(dB) = 10 \times \log_{10}(\sigma^{\circ})$$
 Equation 10.1

In the first instance, no compensation for incidence angle was undertaken. For the PSU columns within the AIRSAR strips, the incidence angle varied from  $26.6^{\circ}-59.9^{\circ}$  (Table 10.1), although no PSUs were observed in the incidence angle ranges of <  $26.6^{\circ}$ ,  $34.9^{\circ}-45.8^{\circ}$  and  $50.3^{\circ}-57.4^{\circ}$ . To investigate the influence of incidence angles on the relationships between SAR backscatter and biomass, data were extracted separately from each of the 10 PSU columns. Columns 3 and 8 were each observed within two AIRSAR strips but, for this analysis, data were extracted only from cm6367/cm6376 (Column 3) and cm6332/cm6333 (Column 8) respectively.

A Cross-Track Illumination Correction (CTIC) was undertaken subsequently to provide some compensation for incidence angle. First, along track mean values were calculated from each of the images and then plotted to observe the variation in the cross track direction. A 3<sup>rd</sup> or 4<sup>th</sup> order polynomial trendline was then fitted and used subsequently to remove the variation across the track. These procedures were undertaken within ENVI and on advice from JPL. Prior to extraction of AIRSAR data (with and without CTIC), all data (~ 5 m) were registered to the map base and then aggregated to 10 m pixel resolution, mainly to reduce speckle noise. Scatterplots were then established, by woodland community, between the AIRSAR backscatter (with and without CTIC) at different frequencies and polarisations and the lidar-derived estimates of biomass. Similar plots were also established with FPC, derived using relationships established with Landsat ETM+ data.

	Inc	Incidence angle range					
Column no.	1	2	3				
cm6367/cm6376	58.1 º - 59.9º	47.5 º - 50.5 º	29.8 º - 34.9º				
Column no.	3	4	5				
cm6354/cm6355	26.6 ° - 31.0 °	45.8° - 48.3°	57.2 º - 58.8 º				
Column no.	6	7	8				
cm6332/cm6333	57.8 º - 60.0 º	46.0 ° - 49.3 °	30.3 º - 33.8 º				
Column no.	8	9	10				
cm6327/cm6331	27.3 º - 32.6 º	46.1 ° - 49.0 °	57.4 ° - 59.0 °				

 Table 10.1
 AIRSAR incidence angles for each PSU column

## **10.4** Relationships between SAR backscatter and biomass

For each of the 10 columns, scatterplots showing the relationship between SAR backscatter and above ground biomass were established using data with and without CTIC. An example of the relationship between non-CTIC SAR data and biomass is shown in Figure 10.5 (Column 1) whilst the relationships between SAR backscatter (both non-CTIC and CTIC) and biomass for remaining columns are shown in Appendix C. The legend for the species present in these relationships is also located in Appendix A.

In all images and at all wavelengths and polarisations, a general increase in SAR backscatter with biomass was observed. However, the strength of the relationship varied with incidence angle (in the case of non-corrected data), frequency and polarisation. Furthermore, the saturation levels at C-band, L-band and P-band differed from those reported in many studies. The following subsections consider each of these in turn.

## 10.4.1 Influence of incidence angle

At most frequencies and polarisations, an increase in SAR backscatter with biomass was observed, with the relationships being particularly prominent within cm6367/cm63676 where extensive areas of bare ground/grassland and regenerating woodlands occurred (Figure 10.1). However, relationships between SAR backscatter (at all wavelengths and polarisations) were generally more coherent at large incidence angles (i.e., 57.4-59.9°) and, as the incidence angle decreased, greater scatter was generally observed. A reduction in the dynamic range of the SAR data was also evident at the lower incidence angles.





To further investigate the influence of incidence angle, the SAR backscatter (at all frequencies and polarisations) associated with non-forested areas was compared between the PSU columns. For some columns, few areas of non-forest occurred and data were therefore extracted from areas known to be known forest (from analysis of Landsat data) north or south of the individual PSUs (but outside the actual PSUs). Data were also extracted from Columns 3 (cm6354/cm6355) and 6 (cm6332/cm6333).

The comparison indicated that, at C-band HH and VV, SAR backscatter generally increased at lower incidence angles whilst at C-band HV, these differences were less obvious (Figure 10.6; Table 10.2). At L-band HH and VV, a similar increase in SAR backscatter with decreasing incidence angle was also evident although L-band HV did not exhibit a marked difference with incidence angle. At P-band, differences in HH, VV and HV polarisation with incidence angle was not particularly evident. Within the CTIC data (Figure 10.7; Table 10.3), these differences in incidence angle had been moderated although not completely removed.

To establish whether SAR backscatter from the vegetated surfaces varied with incidence angle, an upper bound of the backscatter needed to be established. For this purpose, the level at which the SAR backscatter saturated with increasing biomass was considered an appropriate measure. A number of approaches to fitting a non-linear curve to describe the relationship between the SAR backscatter and biomass were considered, including the use of logarithmic and polynomial functions (e.g., Rignot et al. 1994, Santos et al. 2003). However, these were found to be inappropriate for describing the relationship, particularly as they often failed to adequately describe the increase in SAR backscatter with biomass up to the level of saturation. For this reason, a non-linear equation was developed and fitted using the Origin software.



Figure 10.6 Frequency histograms of non-CTIC SAR backscatter at different frequencies and polarisations for the PSU columns (numbered 1 10). Note that Columns 3 and 8 were observed twice

	CHH	CVV	CHV	LHH	LVV	LHV	PHH	PVV	PHV
COL 1	-								
Mean	-12.35	-11.41	-19.59	-21.40	-24.10	-32.88	-25.17	-20.94	-24.35
Mean + SD	-11.51	-10.93	-18.98	-19.58	-23.00	-31.23	-23.63	-17.96	-22.79
Mean - SD	-13.40	-11.96	-20.31	-24.59	-25.58	-35.57	-27.57	-40.34	-26.80
COL 2	10110		20101		20100		21101	10101	20100
Mean	-12.31	-12.60	-21.67	-18.09	-21.77	-31.09	-17.58	-22.28	-32.96
Mean + SD	-11.70	-12.16	-21.02	-16.50	-20.98	-29.87	-15.40	-21.27	-31.25
Mean - SD	-13.03	-13.10	-22.44	-20.63	-22.74	-32.80	-22.16	-23.60	-35.82
COL 3									
Mean	-8.85	-9.22	-19.97	-15.90	-17.29	-28.86	-17.87	-20.11	-32.19
Mean + SD	-8.36	-8.70	-19.22	-15.16	-16.57	-27.90	-16.53	-19.12	-30.86
Mean - SD	-9.41	-9.80	-20.87	-16.80	-18.16	-30.10	-19.81	-21.38	-34.12
COL 4									
Mean	-9.73	-11.65	-19.22	-16.01	-19.23	-27.83	-15.42	-20.95	-31.23
Mean + SD	-9.08	-10.98	-18.26	-15.05	-18.40	-26.36	-13.84	-19.69	-29.54
Mean - SD	-10.49	-12.45	-20.45	-17.24	-20.25	-30.08	-17.92	-22.74	-34.06
COL 5									
Mean	-12.75	-11.69	-20.34	-18.21	-22.00	-32.56	-17.15	-22.56	-34.06
Mean + SD	-12.14	-11.22	-19.66	-16.62	-21.09	-31.13	-14.83	-21.07	-32.25
Mean - SD	-13.46	-12.23	-21.16	-20.73	-23.16	-34.73	-22.46	-24.84	-37.22
COL 6									
Mean	-13.52	-13.96	-21.60	-21.85	-23.41	-32.20	-21.49	-23.73	-33.21
Mean + SD	-11.48	-12.58	-19.49	-18.95	-21.59	-28.86	-18.24	-21.95	-30.88
Mean - SD	-17.52	-16.01	-25.89	-34.84	-26.60			-26.81	-38.56
COL 7									
Mean	-12.87	-12.75	-21.73	-21.74	-23.02	-32.93	-22.36	-24.16	-36.91
Mean + SD	-12.05	-12.01	-20.94	-19.73	-21.75	-30.93	-19.65	-22.67	-33.80
Mean - SD	-13.87	-13.64	-22.71	-25.62	-24.81	-36.75	-31.02	-26.44	
COL 8									
Mean	-7.84	-8.32	-17.40	-14.77	-16.77	-27.18	-17.50	-22.03	-32.42
Mean + SD	-7.10	-7.73	-16.04	-13.63	-15.99	-25.84	-15.69	-20.80	-30.90
Mean - SD	-8.72	-9.00	-19.39	-16.33	-17.72	-29.10	-20.67	-23.74	-34.76
COL 9									
Mean	-9.18	-11.12	-18.35	-15.84	-18.34	-26.51	-15.19	-20.93	-29.31
Mean + SD	-8.51	-10.43	-17.48	-14.78	-17.47	-25.28	-13.44	-19.84	-28.19
Mean - SD	-9.96	-11.95	-19.45	-17.24	-19.43	-28.23	-18.18	-22.37	-30.80
COL 10									
Mean	-8.86	-10.88	-16.65	-15.55	-18.85	-24.76	-15.47	-21.14	-28.34
Mean + SD	-8.16	-10.17	-15.93	-14.62	-17.92	-23.61	-13.90	-19.96	-27.10
Mean - SD	-9.69	-11.74	-17.52	-16.73	-20.04	-26.34	-17.96	-22.78	-30.09
Non Forest									
Mean	-8.85	-9.22	-19.97	-15.90	-17.29	-28.86	-17.87	-20.11	-32.19
Mean + SD	-8.36	-8.70	-19.22	-15.16	-16.57	-27.90	-16.53	-19.12	-30.86
Mean - SD	-9.41	-9.80	-20.87	-16.80	-18.16	-30.10	-19.81	-21.38	-34.12

Table 10.2Mean and standard Deviations for non-forested areas within Columns<br/>1-10 of the non-CTIC SAR data



Figure 10.7 Frequency histograms of non-CTIC SAR backscatter at different frequencies and polarisations for the PSU columns (numbered 1 10). Note that Columns 3 and 8 were observed twice

	CHH	CVV	CHV	LHH	LVV	LHV	PHH	PVV	PHV
COL 1									
Mean	-13.38	-13.21	-21.88	-	-27.35	-	-	-	-
Mean + SD	-12.34	-12.50	-20.89	-25.53	-25.27	-	-	-24.83	-
Mean - SD	-14.75	-14.06	-23.15	-	-31.50	-	-	-42.14	-
COL 2									
Mean	-11.58	-11.74	-20.74	-16.82	-20.90	-29.82	-15.34	-21.33	-31.48
Mean + SD	-10.87	-11.16	-19.81	-15.07	-20.03	-28.31	-12.71	-19.80	-29.50
Mean - SD	-12.42	-12.41	-21.93	-19.82	-21.98	-32.16	-23.09	-23.71	-35.25
COL 3									
Mean	-11.04	-10.40	-21.54	-17.60	-19.02	-31.63	-19.11	-22.90	-35.44
Mean + SD	-10.30	-9.58	-20.52	-16.10	-17.14	-29.18	-17.31	-21.94	-32.75
Mean - SD	-11.93	-11.41	-22.88	-19.89	-22.42	-37.81	-22.22	-24.15	-43.82
COL 4									
Mean	-9.87	-11 65	-19 26	-16 04	-19 23	-97 99	-15 23	-20.83	-31 27
Mean $+$ SD	-9.18	-11.05	-18 17	-15 12	-18 40	-26 33	-13 57	-19.46	-29 59
Mean - SD	-10.69	-19 41	-20 72	-17 91	-20 26	-30.69	-17 96	-22.83	-34.06
COL 5	10.00	12.11	20.12	17.21	20.20	00.00	17.00	22.00	01.00
Moon	13.05	13.63	91 90	21 60	22 50	31.88	91 Q <i>I</i>	23.00	31 99
$M_{eqn} \pm SD$	-10.03	-13.03	-21.20	-21.03	-23.33	-31.00	-21.04	-23.90	-34.22
Moon SD	-10.33	-12.13	-10.54	-10.03	-21.02	-20.20	-10.47	-21.30	-51.75
	-17.35	-15.96	-26.15	-	-27.28	-	-	-21.73	-40.22
COL 6									
Mean	-13.06	-12.57	-21.31	-18.36	-21.90	-32.81	-17.74	-21.83	-34.59
Mean + SD	-12.43	-12.14	-20.69	-16.64	-20.94	-31.16	-15.36	-20.17	-32.60
Mean - SD	-13.80	-13.03	-22.04	-21.24	-23.15	-35.50	-23.39	-24.55	-38.36
COL 7									
Mean	-12.39	-12.01	-21.21	-21.90	-22.83	-32.97	-22.15	-24.51	-36.73
Mean + SD	-11.54	-11.31	-20.41	-19.93	-21.69	-30.95	-19.35	-23.34	-33.75
Mean - SD	-13.44	-12.85	-22.20	-25.61	-24.39	-36.87	-32.31	-26.11	-54.14
COL 8									
Mean	-10.03	-10.08	-18.96	-15.09	-18.94	-27.48	-15.82	-22.86	-31.99
Mean + SD	-9.27	-9.46	-17.58	-13.96	-18.22	-26.01	-14.04	-21.73	-30.23
Mean - SD	-10.96	-10.81	-20.99	-16.63	-19.81	-29.73	-18.89	-24.39	-35.00
COL 9									
Mean	-8.82	-10.45	-17.77	-15.32	-17.63	-25.86	-14.46	-20.15	-28.30
Mean + SD	-8.13	-9.75	-16.89	-14.27	-16.76	-24.64	-12.73	-19.04	-27.17
Mean - SD	-9.64	-11.29	-18.86	-16.71	-18.72	-27.55	-17.38	-21.64	-29.84
COL 10									
Mean	-9.03	-11.07	-17.26	-16.32	-19.60	-25.97	-16.97	-21.78	-29.89
Mean + SD	-8.32	-10.34	-16.53	-15.38	-18.66	-24.80	-15.39	-20.59	-28.64
Mean - SD	-9.88	-11.93	-18.14	-17.51	-20.81	-27.58	-19.46	-23.42	-31.66
Non Forest									
Mean	-8.85	-9.22	-19.97	-15.90	-17.29	-28.86	-17.87	-20.11	-32.19
Mean + SD	-8.36	-8.70	-19.22	-15.16	-16.57	-27.90	-16.53	-19.12	-30.86
Mean - SD	-9.41	-9.80	-20.87	-16.80	-18.16	-30.10	-19.81	-21.38	-34.12

Table 10.3Mean and standard deviations for non-forest areas within Columns 1-<br/>10 of the CTIC SAR data
The equation developed was of the form:

SAR backscatter = 
$$B_s + ((B_n - B_s) \times \exp(-k \times BM))$$
 Equation 10.2

Where B<sub>s</sub> and B<sub>n</sub> represent the SAR backscatter from a forested and nonforested surface respectively and k represents a coefficient that describes the gradient of the curve as it tends towards an asymptote. The fitting procedure aimed to identify values of B<sub>s</sub>, B<sub>n</sub> and k such that the sum of the squares of the deviations of the theoretical curve (Equation 10.2) from the actual independent data points, as indicated through the chi-square statistic, was at its minimum (Microcal 1997). As there was a far greater proportion of high (> 100 Mg ha<sup>-1</sup>) forest and non-forest SAR backscatter values within the data, the relationship was established between the average backscatter extracted for each biomass class (< 1, 1-2, 2-3 etc., Mg ha<sup>-1</sup>) and the biomass. This resulting line of best fit was then superimposed over the scatterplot relating actual SAR backscatter and biomass (Figure 10.8). In all cases, the line of best fit was considered to well represent the relationship. However, when fitting the equation, the mean SAR backscatter value associated with non-forest, which differed between frequencies and polarisations, was not allowed to vary as these values had been established in the previous analysis. Hence all subsequent curves were fitted based on this condition. A benefit of establishing the equations was that the level of saturation in the relationship between SAR backscatter and biomass could also be determined.

For each column, the relationships between SAR backscatter at all frequencies and polarisations (based on non-CTIC data) was established and compared. The analysis highlighted some discrepancies with cm6327 and cm6331 (columns 9 and 10).





Further investigations revealed that the data were incorrectly calibrated and at the time of writing, these two scenes are being reprocessed by JPL. The comparison for columns 1-8 (Figure 10.9), however, provided a unique insight into the influence of incidence angle on the SAR backscatter-biomass relationship.

At C-band HH, the SAR backscatter from non-forest areas was lower at high (57.2-59.9°) incidence angles compared to the lower (29.8 – 34.9°). The difference in backscatter between the non-forested and forested surfaces was also greatest at the higher incidence angles. At medium incidence angles (45.8-50.5°), the SAR return from vegetated surfaces was generally less than at higher incidence angles. At C-band VV, the difference in the SAR backscatter between woodland and bare ground was greatest and least at high and low incidence angles respectively. The range in backscatter at C-band HV was similar at both high and low incidence angles (particularly for higher biomass woodlands). The C-band HV values were also similar for non-forest areas, although slightly higher at low incidence angles.

At L-band HH, the sensitivity of the SAR backscatter to biomass was greatest at high incidence angles and least at low incidence angles. There was a greater similarity in the relationships at high and medium incidence angles. At L-band VV, the overall dynamic range was reduced considerably compared to L-band HH (~ 10 dB compared to ~14 dB). Again, sensitivity to biomass was greater at high incidence angles. At L-band HV, the overall dynamic range was greater compared to L-band HH and VV, with greatest sensitivity at high and, to a lesser extent, medium range incidence angles. Furthermore, there was less variability in the relationship at L-band HV backscatter between different incidence angles.

#### **Chapter 10 Empirical Relationships**



Figure 10.9 Best-fit equations for the relationship between SAR backscatter and biomass for PSU columns 1-8 observed at different incidence angles (see legend below)

At P-band HH, sensitivity to biomass was noticeably greater at high incidence angles. The overall range of backscatter was also high (~ 20 dB) compared to low incidence angles (~ 7.5 dB). At P-band VV, the overall range was reduced considerably (to ~ 10 dB) and the return from non-forest areas was similar regardless of incidence angle, although slightly lower at high angles. At P-band HV, the overall dynamic range was again high (~ 16 dB), and greatest at high incidence angles. The return at high incidence angles was more similar between columns compared to other frequencies and polarisations.

The analysis illustrates that the retrieval of biomass is best achieved using SAR backscatter data acquired at a high incidence angle, regardless of frequency and polarisation, primarily because of the greater dynamic range of the data. As the frequency decreases (i.e., towards L- and P-band), VV polarisation data are less suited for retrieving biomass compared to HH and HV data. HV data are perhaps optimal for the retrieval of biomass, particularly at these lower frequencies, as there appears to be a lesser dependence on incidence angle and the range of data is greater compared to other polarisations. This is supported by the relationships observed between the field-based estimates of component biomass and SAR backscatter which were stronger at HV polarisations. However, HH polarisations, particularly at moderate to high incidence angles, are also appropriate although the range is often slightly reduced.

The moderation of incidence angle effects was achieved partly by applying CTIC. Such a correction is considered necessary for mapping biomass across the landscape from AIRSAR data. However, selecting the most appropriate frequency and polarisation and also equation for spatially estimating biomass, is however, difficult given the across track variability in the AIRSAR backscatter, even after CTIC. This problem is addressed more fully in Chapter 12.

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#### 10.4.2 Levels of saturation

The biomass at which the SAR backscatter at different frequencies and polarisations saturated was determined by identifying where the rate of change in the line of best fit was less than 0.1 dB. The saturation levels between columns were variable but generally increased at lower frequencies (Table 10.4) and did not seem to vary consistently with incidence angle. The general trends were highlighted by taking both the average and maximum of the backscatter saturation level for each PSU column (Table 10.5).

In general, C-band co-polarised data saturated at about 46 Mgha-1 (Maximum 55-60 Mgha-1). However, C-band HV backscatter saturated at 58 Mg ha-1 (Maximum 75 Mg ha-1). L-band saturation was similar at ~ 72-75 Mg ha-1, regardless of polarisation. However, the maximum biomass at which saturation occurred was at L-band HV at 95 Mg ha-1. This higher level of saturation occurred at ~ 45-50° incidence (columns 3 and 4) and was relatively higher at this incidence angle range in Column 7. At P-band, saturation occurred at a level for P-band HH and VV that was similar to that observed using L-band copolarised data. However, P-HV saturation was significantly greater at 113 Mg ha-1 (Maximum of 150 Mg ha-1). This higher level of saturation occurred at incidence angles of greater than 46°. In contrast to many studies, saturation levels at C-band HV were more similar (i.e., maximum of > 75 Mg ha<sup>-1</sup>) to Lband (all polarisations) and P-band (with the exception of HV), suggesting a reasonable relationship with biomass can be obtained. For spatially mapping biomass, P-band HV is optimal because of the greater dynamic range and also the relatively high level of saturation. However, L-band HV data are also considered appropriate.

	C1	C2	C3	C4	C5	C6	C7	C8
	58.1 -	47.5 -	29.8 -	45.8 -	57.2 -	57.8 -	46.0 -	30.3 -
	59.9	50.5	34.9	48.3	58.8	60.0	49.3	33.8
СНН	55	60	40	55	45	40	55	20
CVV	55	55	40	55	55	35	55	20
CHV	70	75	65	60	60	40	65	30
LHH	75	75	85	75	65	75	80	55
LVV	80	75	85	85	80	70	60	40
LHV	80	90	85	95	75	65	75	35
PHH	75	60	90	80	65	80	85	60
PVV	75	45	100	80	70	75	15	45
PHV	145	105	125	105	120	125	150	30

Table 10.4Observed levels of saturation in the relationship between SARbackscatter and biomass. The PSU columns and incidence angles (°) are indicated

Table 10.5Average and maximum biomass (Mg ha-1) at<br/>which the SAR backscatter saturates

	CHH	CVV	CHV	LHH	LVV	LHV	PHH	PVV	PHV
Average	46	46	58	73	72	75	74	63	113
Maximum	60	55	75	85	85	95	90	100	150

#### 10.5 The influence of woodland structure of relationships with biomass

In Chapter 9, the distribution of biomass within different woodland communities (Table 9.1) was highlighted. This distribution was reflected in the relationships between SAR backscatter and biomass, with most of the lower (< 20 Mg ha<sup>-1</sup>) biomass forests dominated by A. harpophylla, Acacia spp. (Wattle), E. mitchelli and E. melanophloia, contributing low SAR returns at all wavelengths and frequencies. Similarly, higher (> 100 Mg ha<sup>-1</sup>) biomass forests dominated by C. glaucophylla, E. melanophloia and A. leiocarpa exhibited greater SAR backscatter. In the intermediate (20-100 Mg ha-1) biomass range, species such as E. populnea, E. melanophloia and other Eucalyptus species were the main contributors to the SAR returns. Although a general increase in SAR backscatter was observed with increasing biomass, considerable variability in the relationships was observed for all columns. This variability was attributed to the wide range of structures existing within woodlands, although different communities of varying structure and supporting similar biomass could not be discriminated. The analysis suggested that discrimination of communities and structures was only possible using the observed relationships by considering different quantities of biomass. The discrimination of woodland communities on the basis of biomass alone was, however, considered to be an unreliable approach.

#### 10.6 Relationships between SAR data and FPC

For most columns, a steady increase in SAR backscatter (all frequencies and polarisations) with FPC (which rarely exceeded 50 % at Injune) was observed. The relationship between SAR backscatter and FPC was considered more useful for discriminating woodland communities as differences between woodland communities were quite pronounced. As an example, Figure 10.10 shows the relationship between SAR backscatter and FPC (cm6376; column 3) and a distinction between woodlands dominated by C. glaucophylla, E. melanophloia or other Eucalyptus species (high biomass with FPC >  $\sim$ 38%), A. leiocarpa (high

biomass but FPC of 30-35 %), E. populnea (medium biomass and FPC of 15-30 %) and regrowth/non forest (low biomass and FPC < 10 %).







Figure 10.11 The relationship between foliage biomass and both a) Foliage Projected Cover (FPC) and b) above ground biomass, as estimated independently for each of the 34 SSUs sampled in the field

a)



Figure 10.12 The relationship between above ground biomass and FPC as determined using a) data derived from the 34 SSUs sampled in the field and b) the lidar estimates of FPC and biomass which were derived using separate regression relationships (See Appendix A for Legend explaining species codes)

a)

A greater correspondence between FPC and C-band HV backscatter was noticeable compared to other frequencies and polarisations, although in all cases, the increase in backscatter with FPC was steady suggesting that increases in FPC corresponded to increases in woody biomass. This correspondence was confirmed in two ways. First, the estimates of FPC from the 34 SSUs sampled in the field were plotted against the derived estimates of leaf (Figure 10.11a) and total (Figure 10.11b) biomass, illustrating that leaf biomass increased with FPC and that total above ground biomass similarly increased in proportion with leaf biomass. FPC was also shown to increase with total above ground biomass (Figure 10.12a). Second, the estimates of FPC and total above ground biomass derived from lidar data were plotted to reveal a similar increase in FPC with The only exception was for associations with A. biomass (Figure 10.12b). leiocarpa where increases in biomass did not result in such a marked increase in FPC (Figure 10.13). Indeed, woodlands with A. leiocarpa associations generally supported a low (< 40 %) FPC compared to woodlands of similar biomass (e.g., C. glaucophylla and E. melanophloia associations where the FPC tended to exceed 40 % and a dense foliage cover was observed). This might be expected given the more expansive open canopies associated with large A. leiocarpa trees and the predominantly vertical orientation of the foliage.

Some anomalies in the relationship between SAR backscatter and FPC were highlighted. In areas of A. harpophylla regrowth, an increase in C-band backscatter (particularly at HV polarisations) with FPC was evident (Figure 10.14). However, at both L and P band, backscatter from A. harpophylla regrowth was similar to non-vegetated areas. In contrast, the backscatter from low biomass E. mitchelli, Acacia spp. (Wattle) and E. melanophloia regrowth increased with FPC. These differences were attributed to the differing structures of the vegetation and the inherent relationships between leaf and branch biomass.

In Section 9.4 (Chapter 9), differences in the allocation of biomass to the leaf, branch and trunk components within and between species were illustrated. In the early stages of growth, BGL allocates a significant proportion (> 50 %) of the biomass to foliage components with the remainder allocated largely to the branches (Figure 10.15a). This allocation is high as most individuals support many small multiple stems. The trunk represents a minor component of the biomass, particularly in the early stages of growth. In contrast, species such as E. mitchelli, E. melanophloia and Acacia spp. (Wattle) allocate a far greater proportion of the biomass to the trunks and are generally single stemmed although multiple stems (rarely more than 5) may occur (Figure 10.15b). Although woodlands containing these species may be of similar biomass and also FPC, the allocation of biomass differs markedly.

As C-band frequencies are generally sensitive to leaves and small branches, the stronger relationships between FPC and C-band backscatter (particularly HV) can be expected. However, at L-band and P-band, the woody structures within A. harpophylla regrowth are generally too small to invoke a response and these areas of vegetation therefore effectively exhibit the same low response as non-vegetated surfaces. This phenomenon is illustrated further in Figures 10.16 and 10.17. Figure 10.16 displays an FPC map of areas of A. harpophylla regrowth, which may be as high as 40 % because of the dense leaf cover. Figure 10.17 demonstrates that C-band, L-band and P-band (HV, VV and HH) composite images reveal a high return from A. harpophylla regrowth at C-band, minimal return at L-band and virtually no return at P-band. In contrast, in low biomass woodlands dominated by, for example, E. melanophloia, E. mitchelli and/or Acacia spp. (Wattle), L-band and P-band microwaves interact with the larger (albeit fewer) trunks of individual trees due to their larger size, and a return is thereby recorded.





Figure 10.13 a) Relationship between Foliage Projected Cover (FPC) and Above Ground Biomass (Mg ha<sup>-1</sup>) for species associations that include SBA and b) illustration of the open canopies of large biomass SBA individuals



harpophylla, C. glaucophylla, Eucalyptus spp., E. populnea, A. leiocarpa, E. melanophloia, E. mitchelli and Wattle. Note that these data Figure 10.14 Relationships established for cm6367 (column 3) between SAR backscatter and FPC by woodland community. A. have been corrected using for cross-track illumination. (See Appendix A for Legend)



Figure 10.15 a) A. harpophylla regrowth with large leaf biomass and large number of multiple stems of small (< 3-5 cm) diameter. b) E. mitchelli clusters supporting similar leaf biomass but fewer stems of greater diameter

b)

a)



Figure 10.16 a) Foliage Projected Cover (FPC) image of **A. harpophylla** regrowth derived using a relationship between lidar-derived FPC and Landsat ETM+ band 5 and the NDVI and b) Shaded image of FPC with green representing an FPC of approximately 40 %.

a)





A second anomaly was observed for woodlands where Acacia spp. (Wattle) was the dominant species (Figure 10.18). Within these woodlands, FPC was typically between 45 and 50 %. At C-band, backscatter was high for these woodlands at all frequencies but noticeably greater at CHH and CVV compared to CHV. However, at both L and P-band, backscatter was noticeably lower (with the exception of P-band HV) as these woodlands generally supported a biomass < 50 Mg ha<sup>-1</sup>. The raised return at P-band is unusual but could be attributed to ground surface or over storey interactions. The large C-band return was considered to be a function of the high foliage cover for Acacia spp., (Wattle) which is a shrub with an expansive canopy (Figure 10.19), consisting largely of small branches which extend to the ground such that there is little trunk volume.



Figure 10.18 Relationships established for cm6333 (column 6) between SAR backscatter and FPC by woodland community. Note that these data have been corrected using for cross-track illumination. Of particular interest are the Acacia spp. (Wattle) communities which exhibit a low biomass and low return but high FPC. (See Appendix A for Legend)



Figure 10.19 Photograph of *Acacia spp.* (Wattle), which is an expansive shrub of high foliage cover but low biomass

## 10.7 Summary

In this chapter, empirical relationships between SAR backscatter at different frequencies and polarisations and both above ground biomass and FPC have been illustrated. The analysis has confirmed the following:

• SAR backscatter increases with above ground and component biomass at all frequencies and polarisations. However, establishing the true nature of interaction of microwaves with the woodland canopy is complicated by the inherent relationships between the biomass of the different components. For this reason, simulation of the backscatter through forward modelling is advocated.

- The relationship between SAR backscatter and biomass is best described by fitting a curve through chi-square minimization.
- The relationship between SAR backscatter and biomass is highly dependent upon incident angle, with stronger relationships obtained at higher incidence angles. At these higher incidence angles also, the dynamic range of the data is also greater. The dynamic range is also greatest at HV polarisations, particularly at higher levels of biomass.
- The biomass at which the relationship with SAR backscatter saturates is approximately 40-50 Mg ha<sup>-1</sup> and 75 Mg ha<sup>-1</sup> for C-band co-polarised and cross-polarised data respectively. L-band (co-polarised) saturation occurs at a higher biomass (~ 70-75 Mg ha<sup>-1</sup>) although can approach 95 Mg ha<sup>-1</sup> at HV polarisations. Co-polarised P-band data exhibits a similar saturation to L-band but the HV polarisation allows estimation of biomass, potentially up to 150 Mg ha<sup>-1</sup>.
- The higher level of saturation of C-band HV data suggests a stronger relationship compared with the co-polarised data and also a link between foliage cover and biomass. This link is supported by both field and lidar-derived observations. The higher level of saturation observed conflicts with other studies of coniferous forests/plantations and tropical regenerating forests, for example, where saturation levels approximating 20 Mg ha<sup>-1</sup>, 60 Mg ha<sup>-1</sup> and 100-150 Mg ha<sup>-1</sup> are commonly reported. The differences in the observed levels of saturation could be attributable to the openness of the canopy and the close correspondence between foliage cover and biomass.
- For these same reasons, a strong relationship between FPC and SAR backscatter at all wavelengths and polarisations was observed. The integration of FPC and SAR backscatter data provided a greater

opportunity for discriminating woodland communities and structures. In particular, significant opportunities exist for mapping woody and nonwoody regrowth using a combination of SAR and FPC data.

A limitation of using empirical relationships, as illustrated in this Chapter, is that the interaction of microwaves of different length and polarisation with the different components (leaves, branches and trunks) of the woodlands could not be easily discerned, due partly to the inherent relationships between leaf, branch and trunk biomass. For this reason, modelling of the SAR return from woodlands of differing structure and biomass was undertaken. The parameterisation of the model and comparison of simulated versus actual SAR backscatter are discussed in the next two chapters.

# Chapter 11

## **Model Parameterisation**

### 11.1 Overview

Although empirical relationships have been established between SAR backscatter and both above ground biomass and FPC, a better understanding of the interaction of microwaves with different components of the vegetation canopy can be achieved through SAR backscatter modelling.

This chapter provides an overview of the structure of the woodlands with a view to parameterising a SAR backscatter model, namely that developed originally by Durden et al. (1989). Using the available plot data, attention focuses on quantifying the dielectric properties of the vegetation and soil, the size and orientation of scatterers (i.e., leaves, branches and trunks) and the roughness of the surface.

## 11.2 Overview of forest scattering model

The model employed to simulate the backscatter from the Injune study site is an adaptation of the model formulated by Durden et al. (1989, 1991), designed specifically for the modelling of the forest backscatter polarisation dependence. It is an electromagnetic scattering model, consisting of two layers over a rough dielectric surface. The upper layer represents the canopy of the forest, encompassing (in the case of conifers) vertical dielectric cylinders (trunks), randomly orientated dielectric cylinders (branches) and needles. The ground layer is represented by a rough, dielectric surface, the scattering from which is estimated using the small perturbation model.

At Injune, the parameterisation and implementation of this model is complicated due to the complex structure and mixed species composition of the woodlands. Nevertheless, the extensive ground data collected at Injune allowed key parameters required for such modelling to be estimated for the woodland types surveyed.

A number of models of microwave interaction with forest canopies have been developed (Chapter 4), although the majority have focused on those comprised of single species, with coniferous plantations (e.g., dominated by pines and spruce) being favoured.

#### 11.3 Parameterisation of model

For parameterisation, the majority of the models require estimates of the dielectric properties, density, size (radius and length) and angle distribution of the main scattering elements (i.e., leaves, branches and trunks). Information on the soil properties (moisture content and roughness) is also needed. The input parameters for the model are entered using the format presented in Figure 11.1. This is an excel worksheet, whereby the figures in bold on the left correspond to the items on the right (e.g., Incidence angle =  $45^{\circ}$ , Canopy thickness = 9.9m).

Most models, including that of Durden et al. (1989), assume a relatively uniform distribution of these scatterers within a volume such that their density is expressed in numbers per m<sup>3</sup>. Often, only one structural type is considered with the forest divided into two basic layers containing the trunk and crown (branches and leaves) respectively. The following sections therefore outline the retrieval of these parameters for the main woodland types.

#### 11.4 Distribution of elements in space

In parameterising the model, the three-dimensional volume within which scattering elements were contained, was determined as the product of the x and y dimensions of the plot (i.e.,  $50 \times 50$  m) and the maximum height of the each

tree form modelled (Figure 11.2). Up to three tree architectures were considered in any one plot, as outlined below.

For each architectural type considered, the canopy layer was contained within this space such that:

$$CLD = HT^{TOP}_{a} - HT_{FLB}_{b}$$
 Equation 11.1

where CLD represents the canopy layer depth,  $HT^{TOP}_{a}$  represents the height (m) of tree <sub>a</sub> and  $HT^{FLB}_{b}$  represents the height (m) of tree <sub>b</sub> to the first leafing branch. The trunk layer depth (TLD) was also calculated for each architectural type by:

$$TLD = HT^{TOP}_a - CLD$$
 Equation 11.2

For hardwoods, it was assumed that the trunk was contained entirely within the trunk layer and the branches and leaves were contained entirely within the canopy layer. For softwoods (i.e., C. glaucophylla), the trunk was assumed to extend to  $\sim 90$  % of the HT<sup>TOP</sup>. For hardwoods, trunks extending into the canopy layer were regarded as branches.

#### 11.5 Selection of Secondary Sampling Units (SSUs)

The model of Durden et al. (1989) was modified (and run) by Mahta Moghaddam of NASA's Jet Propulsion Laboratory (JPL). SSUs were selected such that the main tree's architectures occurring at Injune could be considered, either singularly or in combination. This was achieved by establishing the proportion of 4500 SSUs and 9660 Primary Photo Plots (PPPs) that were represented by the woodlands sampled in the 34 SSUs. The analysis confirmed that approximately 45 % of the woodland communities (defined by considering dominants, co-dominants and understorey species) had been similarly classified as the SSUs (Table 11.1) and that the main structural types were indeed represented.

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45	0.24	5		Incidence angle	Wavelength no	Radii	
9.9	1			Canopy thickness (m)	Softwood (1) Hardwood (2)		
15,3	2.82	0.005		Large branch eps	Length (m)	Radiu	s (m)
0.524	3	50		Large branch density	Pdf exponent	Orient	ation (°)
15,3	1.00	0.0025		Small branch eps	Length (m)	Radiu	s (m)
3.976	3	50		Small branch density	Pdf exponent	Orient	ation (°)
15,3	0.0006135	0.0053	219	Leaf eps	Thickness (m)	Rad.	Density (m <sup>3</sup> )
15,3	5.10	0.0784	0.036	Trunk eps	Height (m)	Rad.	Density (m <sup>2</sup> )

Figure 11.1 Example of input parameters (based on CP-) for the model of Durden et al. (1989)



Figure 11.2 The distribution of scattering elements in the space volume determined from the x and y dimensions (50 x 50 m) of the plot, the top height of the tree forms considered ( $H^{TOP}_{a}$ ) and the depths of the trunk and canopy layers (CLD and TLD respectively). Note that, with each plot, the dimensions of CLD and TLD differed for each tree architectural type considered.

Furthermore, preference was given to SSUs where relatively pure stands of one or several species occurred. On this basis, 114\_19, 148\_16, 114\_12, 114\_4, 111\_12, 142\_18, 23\_15, 81\_11 and 59\_29 were selected as, based on the field data, those that were dominated or co-dominated by C. glaucophylla, A. leiocarpa, E. melanophloia and/or E. populnea.

#### 11.6 Selection of representative trees

Due to the complex structure of the woodlands, representative trees for the different architectures were identified and characterised for the modelling process. The three main architectures considered were small decurrent (e.g., Eucalyptus species), large decurrent (e.g., Angophora species) and excurrent (e.g., Callitris species). In the modelling and for each architecture, trees > and < 10 cm diameter (at 30 cm) were considered separately if occurring within the same plot.

For each architectural type, trees with a leaf, branch and trunk biomass that approximated the average within the selected plot were identified. For the majority of trees, photographs were referenced and compared to confirm whether the structure of trees approximated those of similar size within the rest of the plot. Once selected, the size and density of leaves and branches were estimated based on the biomass of these components.

Woodland communities sampled by the 34 Secondary Sampling Units (SSUs) at Injune. The proportion of the 4500	of Secondary Sampling Units (SSUs) and 9660 Primary Photo Plots (PPPs) associated with these woodland communities is	ated.
ble 11.1 Woodl	lection of Second	o indicated.
Ĩ	Ň	al

		No.	%	No. of	%			No.	%	No. of	% Total
K	(	of.	Total	ΔPI	Total		(	J.	Total	ΔPI	ΔPT
nd Jir	NS אז תא	SSUs	SSUs	units	API		NS או תא	SSUs	SSUs	units	units
nm	sbr nilo 2) ;			(PPPs)	units		sbr nile 2) ;			(PPPs)	(PPPs)
юоо то Это Это Это Это Это Это Это Это Эт	10092 qms2 stinU				(PPPs)	əqvT	10292 Gamg Samu StinU				
C. glaucophylla- E.	$124_{-6}$	484	10.8	1087	11.34	C. glaucophylla - Eucalyptus	$144_{-}19,144$	24	0.5	6	0.01
melanophloia-Eucalyptus spp.						chloroclada-E. melanophloia	$_{-13}_{-5}$				
Non-forest	$59_27, 59_2$	455	10.1	869	9.05	E. melanophloia- A.	$138\_16,138$	22	0.5	16	0.16
	$8,131_{-}27$					leiocarpa-C. glaucophylla	_28				
C. glaucophylla -A. leiocarpa-	$114_{-}12,$	204	4.5	358	3.73	Eucalyptus sppC.	$124\_19$	16	0.4	24	0.25
Eucalyptus spp.	$114_{-4}$					glaucophylla - A. leiocarpa					
C. glaucophylla - Eucalyptus	81_8,	156	3.5	355	3.7	E. populnea- Eucalyptus	$142_{-}2,142_{-}$	14	0.3	13	0.14
spp.	$83_20$					sppAcacia spp.	13				
C. glaucophylla- E.	$83_{-}11$	148	3.3	579	6.03	E. populnea- C. glaucophylla	$148_{21}$	14	0.3	16	0.17
melanophloia						- Eucalyptus spp.					
C. glaucophylla- E.	$111_{-}12,$	139	3.1	273	2.8	C. glaucophylla –Acacia	$81_{-}11$	11	0.2	10	0.1
melanophloia-A. leiocarpa	$111_{-}18$					spp Eucalyptus spp.					
E. melanophloia-C.	$81\_16,138\_$	66	2.2	252	2.6	E. melanophloia - E.	$58_29$	8	0.2	4	0.04
glaucophylla	21					populnea-E.mitchelli					
E. melanophloia-C.	$23\_15$	71	1.6	166	1.7	A. floribunda	$23_{24}$	8	0.2	10	0.1
glaucophylla - Eucalyptus spp.											
A. leiocarpa- Eucalyptus spp	$23_{-}16,$	47	1	06	0.9	E. melanophloia -E.mitchelli	$131_{-}18$	5	0.1	4	0.04
C. glaucophylla	$23\_20$										
E. populnea- Eucalyptus spp.	$148_{-}29$	68	1.5	80	0.83	A. harpophylla-E.mitchelli	$148_{-1}$	2	0.0	2	0.02
E. populnea-E.mitchelli –E. melanonhloia	$148_{-}16$	25	0.6	20	0.2						
E. nonulnea-F. mitchelli	58 24 142	25	0 6	43	0.45						
	$18,142_{-20}$	2									
						PROPORTION OF TOTAL		45.5		44.5	

#### 11.7 Density, size and geometry

#### 11.7.1 Trunks

For each plot, the density of trunks for different groups was based on the number of individuals associated with a particular architecture and expressed as numbers per m<sup>2</sup>. Therefore, for each plot, several densities of trunks were reported depending upon the number of architectures considered. The radius midway along the trunk was calculated from the diameter of the average tree (at 130 cm) multiplied by an adjustment factor (ranging from 0.6 to 0.9), which was estimated from photographs and knowledge of trunk taper. As indicated earlier, the trunk of softwood species extended to 90 % of the HT<sup>TOP</sup>. For hardwoods, the length of the trunk was taken as the HT<sup>FLB</sup> measurement. All trunks were assumed to be vertically orientated.

#### 11.7.2 Branches

For the main structural groups (i.e., pines, eucalpyts and apples), branch geometry was determined by measuring (from available digital photographs) the orientations ( $\phi$ ) of individual branches within selected size classes (< 4 cm, < 10 cm and > 10 cm; Table 11.2). Based on the resulting probability density function (pdf), the pdf exponent was approximated. Examples of the frequency histogram for E. populnea, E. melanophloia, C. glaucophylla and A. leiocarpa are given in Figures 11.4-11.6.

Small and large branches were considered to be 1 cm and > 1 cm in diameter respectively. Based on the available digital photographs, small branch length (BL<sub>s</sub>) was estimated to be ~ 1-1.5 m in length regardless of growth stage. For softwoods and also smaller hardwood species, branches > 10 cm were rare. In these cases, the length of branches > 1 cm in diameter (BL<sub>i</sub>) was determined by dividing the crown radius by the sine of the medium orientation from vertical (e.g., 49.8° in the case of C. glaucophylla) to estimate total branch length (BL<sub>tot</sub>) and then subtracting BL<sub>s</sub> such that:

$$BL_l = BL_{tot} - BL_s$$
 Equation 11.3

Branch radius was assumed to be less than 5 cm. Small and large branch volume (based on a cylinder) was then calculated based on inputs of branch length (m) and radius (m). The biomass of each cylinder was then calculated by multiplying volume by a species- specific wood density

For larger hardwoods, the length of the large branches (which often exceeded 10 cm in diameter) was estimated initially on the basis of crown depth (minus the length of the smaller branches). Similarly, the diameter of the larger branches was approximated to less than half the diameter of the trunk at 130 cm. Based on these initial values, branch volume (based on a cylinder) was calculated and the biomass of each cylinder determined by multiplying the volume by a species specific wood density (g cm<sup>3</sup>; Table 11.3). On this basis, an initial estimate of the number of large branches per tree was derived from the branch biomass (total branch biomass minus the < 1 cm branch biomass) for the tree as estimated using allometric equations. The length and radius of the larger branches were then adjusted iteratively until a realistic number of typical trees were used as reference.

The number of small and large branches was estimated by dividing the total branch biomass (< 1 cm and > 1 cm) for the tree by the biomass of the individual cylinders within each size class. The density of branches (numbers per  $m^3$ ) was calculated by dividing the total number of branches in the canopy (based on the density of trees of each species) by the volume ( $m^3$ ) of the canopy layer.

#### 11.7.3 Leaves

For the species BGL, E. populnea, E. melanophloia and A. leiocarpa, leaf length (mm) and width (mm) measurements were taken from photographs of the leaves, within which a measurement scale was provided (Figure 11.3). From each photograph, leaf dimensions were extracted using the measurement tool within ENVI and a graticule within the photographs as reference. Leaf length was measured along the approximate centre of the leaf from the base of the petiole to the tip (Figure 11.3a), regardless of the condition of the leaves. For example, if insectivores had removed 60 % of the leaf, these leaves were still included in the measurement. Leaf width (m) was measured as the distance from one edge of the leaf to the opposite edge (Figure 11.3b). Leaf radius (m) was then calculated as half the average of the leaf length and width. Average leaf thickness (m) and wet weight (g) were determined from field measurements.

Average leaf dry weight was measured following oven drying of samples. For each species, the density of leaves in the crown was estimated by dividing the dry weight of leaves in the canopy, as estimated from allometric equations, by the dry weight of the individual leaves. The number of leaves in the plot was estimated by multiplying the number of leaves by the number of trees of each species. The density of leaves (number per m<sup>3</sup>) was estimated by dividing the total number of leaves by the canopy layer volume.



Figure 11.3 Procedure for measuring a) the length and b) thickness of leaves, using a leaf of Acacia harpophylla (BGL) as an example.

			Exp		0		>4
		> 10 cm	φ		26.9		21.7
			N		27		34
			Exp	1	1.5	3	2.5
irpa (SBA).		< 10 cm	φ	28.3	31.0	49.8	33.0
na A. leloca	ize Class		Ν	171	128	229	133
'11a (CF-) ai	Branch Si	cm	Exp	4	1	33	2
. glaucopny		4-10	φ	14.9	31.1	49.8	33.9
01a (JJL), U			Ν	54	50	229	59
melanapnio			Exp	2	2	3	3
		< 4 cm	φ	30.6	31.5	49.8	33.6
			N	142	78	229	74
				E. populnea	E. melanophloia	C. glaucaphylla	A. leiocarpa

Branch orientations and pdf exponents for branches within different size classes and for the species E. populnea (PBX), E. malananhoia (STD) and A. Jainema (SRA) Table 11.2

Table 11.3Wood density (g cm-3) by species

Wood density (g cm <sup>-3</sup> )	0.854	0.916	0.745	0.569	0.87
Species	E. populnea	E. melanaphloia	A. leiocarpa	C. glaucophylla	A. harpophylla







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Figure 11.5 Angle distributions of branches a) < 1 to 4 cm and b) > 4 to 10 cm and c) > 10cm for Eucalyptus melanophloia (SLI).

a)

ට







Figure 11.6 Angle distributions of branches a > 1 to 4 cm, b) > 4 to 10 cm and c) > 10 cm for Angophora leiocarpa (SBA).

a)

 $\mathbf{\hat{c}}$ 

## 11.8 Stand parameterisation

For selected SSUs and individually for the main species groups (e.g., pines, eucalypts and angophoras) the dimensions and density of all components (leaves, small and large branches and trunks) were quantified together with the geometry of both small and large branches. When scaled to the plot, the biomass of the individual components for each group equated approximately (generally to within a < 5 Mg ha<sup>-1</sup>) to the biomass of these same components, as calculated for all trees based on allometrics. The parameters are listed in Tables 11.4-11.5. For each SSUs, small branches were those < 1 cm in diameter whilst the larger branches were those greater than 1 cm diameter. As the woodlands were structurally diverse, the size of the large branches was more variable between species and SSUs depending upon the diameter distribution of the trees contained.

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$12, 81_{-}1$	
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(שש) דפּשַ נעזכאַפּעפּצ	0.3	0.6	0.6	0.6	0.6	0.3	0.3	0.6	0.6	0.34	0.37	0.6	0.4	0.3	0.4	0.3	0.6	0.6
(m2)				0.5	0.5	0.3	0.3	0.5	0.5	0.3	0.3					0.3	0.5	0.5
No. Ieaves/tree	56977	44046	0	42009	5530	458	409	41344	3014	42505	2847	82075	3296	316780	5600	44254	80609	7422
8m/səvsəl .oN	22	91	0	760	5	17	13	68	9	23	53	49	7	44	7	27	187	172
(m) Crown Depth	7.7	9.5	0.0	10.0	3.5	11.0	0.8	7.9	3.0	5.7	1.9	9.0	0.8	20.3	5.2	11.6	9.9	2.5
exponent Small branch	2	ŝ	ŝ	3	3	3	2	°	ŝ	3	S	S	S	°	2	1	S	3
Small branch (°) orientation	31.5	50	50	50	50	34	31.5	50	50	34	34	50	50	33.6	31.5	31.5	50	50
Small branch (m) length	1.5	1	1	1	1	1.5	1	1	1	1.5	1	1	1	1.5	1	1.5	1	1
Small branch (mɔ) suiber	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	3	0.5	0.5
No. small branches/ tree	943	812	0	176	113	3883	12	785	64	501	59	1469	38	2839	117	757	1106	150
exbouent Large branch	1	S	ŝ	3	3	4	3	ŝ	S	4	1	ŝ	S	4	1	1	ŝ	3
Large branch orientation (°)	31.1	50	50	50	50	22	34	50	50	21.7	31.5	50	50	21.7	31.1	31.5	50	50
length (m) Large branch	6.2	3.0	0.0	1.7	0	9.5	0.75	2.32	0	4.2	1.85	2.3	0.0	10.8	4.2	5.1	3.82	0
Large branch radius (cm)	5.6	0.5	0.5	0.5	0.0	14.1	0.3	0.5	0.0	3.8	0.3	0.5	0.5	10.9	1.0	3.0	0.5	0.0
branches/tree Vo. Large	5	69	0	112	0	6	0	62	0	9	1	348	0	5	11	67	107	0
(m2) Trunk radius	11.1	7.5	0.0	6.0	2.0	38.0	0.9	6.5	1.7	7.5	0.5	11.1	2.5	22.8	2.0	10.0	7.0	2.5
цэдиэ <b>д א</b> иитТ	3.3	11.0	-1.0	7.0	3.5	13.0	0.8	2.9	3.0	7.6	6.9	13.6	6.8	16.3	8.0	6.6	5.1	2.5
hardwood/ boowbred	Η	S	S	S	S	Η	Η	S	S	Η	Η	S	S	Η	Η	Η	S	S
No. Trees	6	49	201	105	23	1	880	33	42	11	371	30	102	٢	63	18	89	674
Species	E. melanophloia	C. glaucophylla	1 C. glaucophylla	C. glaucophylla	glaucophylla	A. leiocarpa	<sup>1</sup> Acacia neriifolia	C. glaucophylla 1 C.	glaucophylla	A. leiocarpa	<sup>1</sup> A. leiocarpa	C. glaucophylla 1 C.	glaucophylla	A. leiocarpa <sup>1</sup> Acacia	neriifolia	E. melanophloia	C. glaucophylla 1 C.	glaucophylla
Plot	$144_{-}19$	(46)		$114_{-}12$	(25)			114_4	(06)			81_11	(148)			$111_{-}12$	(127)	

 $111_{-}12.$ 

$ (s) \ 148\_16, 58\_29, 142\_18, 142\_2, 142\_20, \\$	
stics of woodlands within Secondary Sampling Units (SSI	00 1F 2 1 1 10 10
Table 11.5 Structural characteri	

Leaf radius (cm) Leaf thickenss (mm)	0.3	0.6	0.6	0.4		0.3	0.3		0.3	0.3	0.3	0.6		0.6	0.3		0.3
No. leaves/tree	56977	42351	486	1516		35785	19870		1790	31293	22210	31521		1573	61033		2056
<sup>s</sup> m/səves/m <sup>3</sup>	57	13	12	19		32	42		64	63	92	49		82	3		32
(m) Crown Depth	11.5	8.2	0.0	0.0		8.6	3.3		3.0	10.1	6.9	7.7		2.5	7.6		2.5
exboueut Small branch	5	ŝ	ŝ	2		2	2		2	2	2	3		°	3		2
Small branch orientation (°)	31.5	50	50	31.5		31.5	30.6		31.5	30.6	30.6	50		50	33.6		31.5
Small branch Small branch	1.5	1	1	1		1.5	1.5		1	1.5	1.5	1		1	1.5		1
Cmall branch (m) suiber	0.25	0.25	0.25	0.25		0.25	0.25		0.25	0.25	0.25	0.25		0.25	0.25		0.25
No. small branches/ tree	943	782	11	11		629	337		48	449	414	591		35	687		53
exboueut Fstê pranch	1	ŝ	3	1		1	1		1	1	1	3		33	4		1
Large branch orientation (°)	31.1	50	50	31.1		31.1	28.3		31.1	28.3	28.3	50		50	21.7		31.1
length (m) Large branch	10.0	3.4	0.0	-1.0		3.6	2.8		2.0	7.6	0.4	3.2		0.0	6.1		1.5
Large branch radius (cm)	6.5	0.5	0.5	0.5		4.6	3.2		0.8	4.2	3.0	3.0		2.0	3.0		3.0
No. Large branches/tree	2	57	0	-11		9	15		1	3	44	34		0	4		1
(cm) Trunk radius	12.9	6.6	0.6	1.0		11.0	8.2		1.4	10.1	6.9	5.0		1.0	9.9		1.7
վդցոցվ հորքի	7.0	10.5	4.9	5.2		4.7	7.6		2.5	4.6	6.9	8.2		4.0	4.8		2.5
Softwood/ boowbred	Н	S	S	Η		Η	Η		Η	Η	Η	S		S	Η		Η
səərT .oN	29	9 72	0 35	8		19	45	77	2	51	80	30	10	60	1	30	1
səicəqZ	E. melanophloia C	C. glaucophylla <sup>1</sup> C.	glaucophylla <sup>1</sup> N.	microcarpa	ц	melanophloia	E. populnea	н Н	melanophloia	E. populnea	E. populnea C.	glaucophylla	<sup>1</sup> C.	glaucophylla	A. leiocarpa	1 E.	melanophloia
Plot	148_16	(02)				$58_{-}29$	(81)			$142_{-}18$	$23_{-}15$	(02)					

23\_15 and 148\_16.

#### 11.9 Dielectric properties of vegetation and soil

Based on trees harvested at Injune, the water content of leaves and both branches and trunks of varying size class was determined. Moisture content was calculated as the difference between the dry and wet weight of the components (by species, where prefixes C, BRI, EPOP and MEL represent C. glaucophylla, A. harpophylla, E. populnea and E. melanophloia), expressed as a percentage (Figures 11.7-11.13).

For all species, leaf water content generally varied between 40 and 50 % although was as high as 60 % for lower diameter (younger) E. populnea trees (Figure 11.7). No differences between species were observed. The water content of branches < 1 cm (Figures 11.8) was slightly lower, varying around 40 %. For trees supporting branches < 1 to 4 cm and 4-10 cm, water content was often lower than 30-35 % and noticeably lower for Eucalyptus species. The water content of the trunks tended to decrease with size (Figures 11.11 to 11.13) with between 12 % and 25 % occurring at the base of largest trees, particularly Eucalypts.

The gravimetric water content of the soil varied from  $\sim 1 \%$  to 13 % and volumetric water content varied from  $\sim 4\%$  to 18 %. Higher moisture contents were generally (although not always) associated with clay soils.

These estimates of moisture content were used to guide the parameterisation of the soil and vegetation inputs for the model of Durden et al. (1989). The real ( $\epsilon$ ') and imaginary ( $\epsilon$ '') parts of the relative complex dielectric constant, which relate to the permittivity and conductivity of the media, was calculated using the relationships established by El-Rayes and Ulaby (1987).















# 11.10 Summary

To support the modelling of microwave interaction with different components of the woodlands, parameters relating to the size, dimensions and geometry of scattering elements (leaves, branches and trunks) and the dielectric properties of vegetation and soil were quantified for selected SSUs. SSUs were selected such that the main structural types were considered.

In undertaking the parameterisation, the full range of data collected in the field was utilised. In particular, forest inventory measurements were used to establish basic parameters such as tree height and diameter and also crown depth. Digital photographs of individual trees were used to establish branch angle distributions and confirm estimates of branch length whilst photographs of leaves were used to establish leaf dimensions. The destructive harvesting data were used to estimate the size, density and moisture content of the major scattering elements. Soil measurements were used to establish moisture content and approximate surface roughness.

In parameterising the models, some homogenisation of woodland structure was necessary. However, the parameterisation was such that the biomass of components within the simulated woodland approximated the biomass of these components estimated using allometric equations. Furthermore, several species (e.g., E. populnea and other Eucalyptus species) were considered to be structurally similar and therefore adequately represented by the parameterisation. The following chapter outlines compares and validates the results of the simulations.

# Chapter 12

# Simulations of SAR backscatter from Woodlands

## 12.1 Overview

Using the adapted model of Durden et al. (1989), the simulation of the SAR return was undertaken by Mahta Moghaddam based on the inputs provided. The main purpose of the simulation was to provide a better insight into microwave interaction within mixed species woodlands and to establish whether differences in scattering mechanisms and return occur between different tree architectures (e.g., as typical to pines, eucalypts and angophoras). The simulation was also undertaken to establish confidence in the use of the model in this environment. The assessment was important as the model could then be used to simulate the SAR return at different frequencies and polarisations using multiple inputs relating to stand parameters, thereby allowing subsequent inversion of the SAR data to retrieve these parameters (Moghaddam and Lucas 2003). This chapter presents and interprets the results of the simulation for the selected woodland types with up to three different architectures present.

### 12.2 Actual versus simulated backscatter

From the simulations, the total SAR backscatter at C-, L- and P-band frequencies and polarisations was determined, from both Cross Track Illumination Corrected CTIC and non-CTIC data, by a) calculating the contributions of volume scattering from the upper crown layer, double bounce scattering between the ground and the branch/and or trunk layers and odd/single bounce scattering from the ground from each species and b) linearly superimposing the like contributions from all species. The interaction of microwaves among the structures associated with different species was not considered. The incidence angles at which the selected SSUs were observed are given in Table 12.1.

Secondary	Column	Incidence	Species	Biomass
Sampling		Angle at which		(Mg ha-1)
Unit		observed		
81_11	1	<b>58</b> °	C. glaucophylla, A. leiocarpa	148
111_12	1	<b>59</b> °	C. glaucophylla, E.	127
			melanophloia	
114_4	4	<b>46</b> °	C. glaucophylla, A. leiocarpa	90
58_29	8	<b>30</b> °	E. populnea, E. melanophloia	81
148_16	8	<b>30</b> °	C. glaucophylla, E.	70
			melanophloia	
23_15	3	33°	C. glaucophylla, E.	
			melanophloia	
142_18	2	<b>49</b> °	E. populnea	60
144_19	4	<b>47</b> °	C. glaucophylla, E.	46
			melanophloia	
114_12	5	<b>46</b> °	C. glaucophylla, A.	25
			leiocarpa, A. neriifolia	

Table 12.1Simulated SSUs, their dominant species and incidence angle at which<br/>they were observed by the AIRSAR

To evaluate the outputs of the simulation, AIRSAR amplitude data at all frequencies and polarisations were extracted from proximal SSUs contiguous with and designated with the same woodland community classification and canopy cover estimate as the 9 SSUs sampled in the field. The mean and standard deviation of simulated and actual backscatter at each frequency and polarisation were then compared.





Using AIRSAR data corrected for incidence angle (CTIC), the correspondence between simulated and actual backscatter distribution at C-band VV and HV polarisations was high, although C-band HH was underestimated (Figure 12.1). In this particular case, the measured C-band HH data were somewhat suspect since there is very little variation in the value of backscatter among all stand types, which could be due to an anomalous recording or calibration of data for that case only. At L- and P-band, simulated and actual backscatter distributions at HH and VV polarisations were similar although at both frequencies, HV backscatter was generally underestimated. A similar correspondence was observed for data not corrected for incidence angle with the exception of L-band HH where greater discrepancies were observed.

These differences were highlighted by a one-way Analysis of Variance (ANOVA), which was performed on the actual CTIC backscatter and simulated backscatter data. At C-band, no significant difference existed between the simulated and actual backscatter for VV and HV polarisations (Table 12.2). However, for HH, the difference between the simulated and actual backscatter was highly significant (p<0.001). The simulation underestimated the HH backscatter. For all woodlands simulated, the mean actual C-band HH backscatter ranged from -6 to -8 dB whilst the simulated return from these same woodlands approximated -6 to -14 dB.

At L-band, no significant difference existed between the simulated and actual backscatter for HH and VV polarisations (Table 12.2). For the cross-polarised (HV) data, the difference between the simulated and actual backscatter was significant (p<0.001). This was evident in the underestimation of the simulated backscatter for HV. Similarly, at P-band, the difference between the simulated and actual backscatter was found to be significant at HV polarisation.

In summary, no significant difference was observed at C-band VV, C-band HV and the co-polarised data at L- and P-band. This correspondence was encouraging given that several complex architectures were considered within each SSU, with the return from each summed to give the total return at each frequency and polarisation. For the remaining frequencies and polarisations, the simulated and actual mean backscatter did not always correspond, although the simulations were generally within the range observed for the woodland types considered.

Table 12.2Single factor Analysis of Variance (ANOVA) for C-, L- and P-band for<br/>each polarisation to test for significant difference ( $\alpha$ =0.05) between simulated<br/>backscatter and actual backscatter at all incidence angles

Frequency/Polarisation	df	F	P-value
C-band HH	27	14.68	0.00072
C-band VV	27	0.74	0.40
C-band HV	27	2.44	0.13
L-band HH	27	0.14	0.71
L-band VV	27	0.39	0.54
L-band HV	27	40.68	9.4E-07
P-band HH	27	0.45	0.51
P-band VV	27	0.39	0.54
P-band HV	27	8.94	0.00603

The apparent discrepancies between the simulated and actual SAR backscatter can be attributed to errors associated with the model inputs, the model itself and the AIRSAR calibration. Specifically, errors were associated with field measurement, the conversion of measurements to distributed parameters for the scattering model inputs and the conversion of moisture content values to dielectric constants. When using the single-species model of Durden et al. (1989), errors in the simulation were expected to be amplified for the multiple species case since the overall return was obtained through linear superposition of the contributions from the each of the single species, and species-species volume interactions were ignored. Furthermore, the forest floor return was assumed to be that due to the contribution from the ground under the higher biomass species present in each of the SSUs, which would lead to an overestimate in ground returns and double bounce scattering (as insufficient attenuation) and an underestimate of volume scattering. This effect was expected to be greatest at all polarisations of C-band, due to the higher sensitivity to the branch layer. The assumption that stems were distributed uniformly within the SSU might also have led to differences between actual and simulated data. Finally, the AIRSAR data are typically quoted as having a calibration accuracy of  $\pm 1$  dB, which should be considered as additional error bars on the observed data values. Discrepancies between simulated and actual mean backscatter were inevitable given the potential sources of error outlined above. However, in general, the correspondence between simulated and actual backscatter at most frequencies and polarisations was considered reasonable for the woodland types considered, particularly given their complexity.

# 12.3 Simulated scattering mechanisms

The backscatter simulations were undertaken to study the scattering mechanisms from a range of woodland types present at the Injune study site. The results of the simulations prove the total backscatter and the relative contribution of each model component to the total backscatter at C-, L- and P-band for all polarisations. As indicated in Chapter 4, the model components (Figure 12.2) and the interactions they represent are:

- Branch/Foliage (Volume scattering)
- Branch/Ground (Double-bounce)
- Trunk/Ground (Double-bounce)
- Ground (Single bounce)



Figure 12.2 Scattering mechanisms described using the model of Durden et al. (1989)

12.4 SAR backscatter from different woodland types.

For each of the simulations and as an output from the model of Durden et al. (1989), the contribution of the different scattering mechanisms to the overall SAR return at different frequencies and polarisations was estimated.

An overview of the species combinations within each of the simulated SSUs has been given in Table 12.1. A pictorial overview of each of the simulated SSUs is given in Appendix D. The contribution through each scattering mechanism as well as the total contribution, at all frequencies and polarisations is also displayed in Appendix D. The backscatter contribution made from the individual species, within these associations was also simulated according to the SSUs at the various wavelengths and polarisations. This is demonstrated in Appendix E.

The following sections consider these contributions from woodlands of varying biomass and containing a) a mix of C. glaucophylla and A. leiocarpa, b) a mix of C. glaucophylla and E. melanophloia and c) E. populnea or a mix of E. populnea and E. melanophloia.

## 12.4.1 Mixed C. glaucophylla and A. leiocarpa woodlands

<u>81\_11</u> This plot contains C. glaucophylla and A. leiocarpa, representing the excurrent and decurrent growth forms respectively. Despite the obvious differences in biomass allocation to the components, the simulated backscatter for all terms is similar for both species. Backscatter from the branch/foliage is strongest for A. leiocarpa and C. glaucophylla at CVV and PHH respectively. The magnitude of the co-polarised backscatter for A. leiocarpa is close at C-band and L-band. However, at P-band, the HH backscatter is stronger. Neither species record a branch/ground response at C-band. At L-band and P-band, the response is similar at all polarisations for both species. However, it is stronger at P-band than L-band, for the HH and VV backscatter. Generally, the trunk/ground response is slightly stronger for C. glaucophylla at HH, yet stronger for A. leiocarpa at VV. The ground response was strongest at C-band, decreasing with an increase in wavelength.

114\_4 In this plot, the foliage backscatter from C. glaucophylla and A. leiocarpa, demonstrate a number of differences, highlighting the sensitivity of the SAR signal to the excurrent and decurrent form. C-band is responsible for the strongest foliage backscatter for both species. Both display a decrease in HV backscatter as the wavelength increases. However, CHV backscatter from A. leiocarpa is considerably weaker than the same from C. glaucophylla. The CVV backscatter from C. glaucophylla is strongest. However, it is only marginally stronger than the C-band co-polarised backscatter for A. leiocarpa, which is equal. Backscatter from the foliage decreases at L-band for both species; however it remains dominant from C. glaucophylla at LVV and increases at Pband to the magnitude of the C-band response. For A. leiocarpa, VV backscatter remained constant at L- and P-band but the HH backscatter increased at Pband. Branch/ground backscatter was strongest at L-band for both species. However, the contribution from A. leiocarpa dominated the total backscatter. A. leiocarpa records no trunk/ground backscatter at C-band. At both L- and P-

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band, the backscatter is strongest at HH polarisation. LHH and LVV backscatter for A. leiocarpa are stronger than the corresponding like-polarised backscatter recorded from P-band. The trunk/ground backscatter for C. glaucophylla is strongest at PVV.

114\_4 was one of two plots simulated which had a stronger PVV backscatter than PHH. In contrast, Wang et al. (1993a) reported that for pine stands, the backscatter from the trunk/ground term is much greater for HH than VV backscatter. It is important to note that the difference between PHH and PVV responses wasn't considerable (<1 dB). For those plots, in which a single species far outnumbers any associated species (e.g., C. glaucophylla 114\_4 and 111\_12), the trunk/ground term totally dominates P-band backscatter at all polarisations. This is not evident for any other of the simulated plots. This may be explained by the difference in the distribution of biomass between decurrent and excurrent forms. C. glaucophylla is representative of the excurrent form and thus, demonstrates a predominate allocation of biomass to the trunk component, facilitating a dominance of trunk/ground backscatter.

<u>114\_12</u> Within the lower biomass (~ 25 Mg ha<sup>-1</sup>) woodland, represented by SSU 114\_12, a significant understorey was observed. Within this woodland, the overall SAR return (at all frequencies and polarisations) was lower compared to the higher biomass woodlands.

In terms of the contribution to the backscatter from the foliage, there exist large differences for the three species simulated. For the hardwoods, the VV backscatter is strongest. The magnitude of the co-polarised backscatter doesn't change as the wavelength increases. For A. leiocarpa, the VV backscatter is also dominant. It is strongest at C-band, decreasing to half its magnitude at L-band, but increasing again at P-band. This is also the trend for the HH response. C. glaucophylla demonstrates a similar trend to A. leiocarpa, however, the PHH backscatter is stronger than CHH.

The foliage interaction dominates the backscatter at all frequencies and polarisations. This is largely due to the lack of large trees and subsequently, a decrease in the trunk/ground interaction.

This plot demonstrated the strongest trunk/ground backscatter for HH and VV at C-band. This may be explained by the open canopy of this woodland (FPC 22%), which comprises three distinct layers. The top layer consists entirely of sparsely distributed A. leiocarpa crowns. The middle layer is comprised of C. glaucophylla, below which lies an understorey of the same species. Thus, the synergy between the open nature of the canopy and the density of trees (14.93 trees/hectare, which is the lowest of all the simulated plots), would have been instrumental in the C-band wavelength penetrating the upper layers and being backscattered as a result of the trunk/ground interaction.

At L-band, backscatter from the trunk/ground term dominates the HH return. The trunk/ground contribution is strongest at PHH for C. glaucophylla. The HH backscatter for A. leiocarpa and the other hardwoods is stronger at L-band for trunk/ground term. Of the species simulated, the backscatter from the ground is strongest at CVV. It is of a similar magnitude for C. glaucophylla, A. leiocarpa and the additional hardwoods present. The ground response decreases with frequency. The backscatter from the branch/ground double bounce interaction is negligible for all species simulated.

# 12.4.2 Mixed C. glaucophylla and E. melanophloia woodlands

<u>111\_12</u> The woodlands sampled in SSU 111\_12 were of relatively high biomass (127 Mg ha<sup>-1</sup>) and consisted of an overstorey dominated by C. glaucophylla but mixed with E. melanophloia and a dense understorey. For this reason, the backscatter from three structures (C. glaucophylla, E. melanophloia and C. glaucophylla understorey) was simulated. This plot had a density of 613 trees/ hectare and a FPC of 44.7%, both of which were the highest recorded of all the simulated woodlands. As a result, the foliage contribution dominated the C-

band backscatter, with insignificant contributions from the other scattering mechanisms, due to attenuation of the SAR signal by the dense canopy. Backscatter was strongest at VV polarisation, with C. glaucophylla being the dominant contributor. The cross-polarised component of the C-band backscatter was stronger than for the other simulated woodland associations, indicating the dominance of volume scattering.

At L-band, the branch/foliage contribution from the C. glaucophylla over storey dominated, particularly at VV polarisation. Ferrazzoli and Guerriero (1995) suggested that the preferential horizontal branching of coniferous species inhibits subsequent backscatter from the layers beneath resulting in VV backscatter being greater than HH at this wavelength, which was evident in this woodland. At all wavelengths, E. melanophloia was responsible for the strongest backscatter from the ground surface.

However, the majority of the L-band and P-band returns originated through trunk/ground interactions, particularly from the larger C. glaucophylla trees which dominated the woodland (89 individuals of C. glaucophylla compared to 18 of E. melanophloia with 674 C. glaucophylla in the understorey).

<u>148\_16</u> The woodlands represented by 148\_16 supported a biomass of approximately 70 Mg ha<sup>-1</sup>. In these woodlands, E. melanophloia dominated (29 individuals compared to 9 of C. glaucophylla). The contribution of the HH and VV backscatter to the branch/foliage term was considerably greater for E. melanophloia than C. glaucophylla at both C- and L-band. The magnitude of the backscatter at both polarisations was similar for E. melanophloia. At P-band, the HH backscatter is stronger than that recorded at C-band for both species.

There is no branch/ground backscatter recorded for either species at C-band. At L- and P-band, the backscatter at both the co- and cross-polarisations is stronger for E. melanophloia than C. glaucophylla. HH backscatter dominates for E. melanophloia. Similarly, there is no trunk/ground backscatter at C-band for both species. Furthermore, both species dominate HH backscatter at L- and P-band, with E. melanophloia responsible for the stronger backscatter at all polarisations.

<u>23\_15</u> This plot records the strongest backscatter from the branch/ground term, at P-band HH. This response is stronger than for any of the other simulated SSUs. It has a density of 214 trees/ha, which is the second most populated plot. As a result, the incident SAR wave is attenuated and subsequently backscattered by the foliage and branch/ground terms. These interactions dominate the backscatter. Thus, a reduced amount of the SAR signal is able to penetrate to the lower levels of the woodland, in order to interact with the trunk and the ground.

For all polarisations at P-band, the backscatter from the foliage is stronger than that from the trunk/ground term. Such a scenario is unique at HH polarisation. However, it is also evident that the contribution to the total P-band backscatter is of a similar magnitude for the foliage, branch/ground and trunk/ground terms.

The biomass of the woodlands sampled within 23\_15 was similar to that of 148\_16 and similar species were contained, although the trees were smaller and the density greater. For both these species within these woodlands, the C-band return as a result of scattering from the foliage was significant. At L-band, a high trunk/ground interaction was observed for both C. glaucophylla and E. melanophloia due perhaps to the greater density of trees of moderate size. At P-band, branch/ground interaction was dominant from the E. melanophloia components but negligible from the C. glaucophylla components. In contrast, trunk/ground scattering dominated the return from C. glaucophylla woodlands at P-band.

<u>144\_19</u> The lower biomass (~ 46 Mg ha<sup>-1</sup>) woodlands sampled by 144\_19 were dominated by E. melanophloia and C. glaucophylla. This plot demonstrates the greatest variability in backscattering mechanisms. At C-band, scattering from the foliage predominates, with VV being strongest, while HH and HV polarisations are of a similar magnitude. Scattering from C. glaucophylla dominated, as these were more abundant (49 individuals compared to 9 E. melanophloia).

At L-band, the dominant contributor to the HH backscatter is the doublebounce trunk/ground interaction. Similar contributions to the HH backscatter are also made by the foliage and ground surface. At VV polarisation, backscatter from the foliage dominates. The branch/ground interaction from E. melanophloia was greater than trunk/ground scattering at all polarisations. In contrast, branch/ground scattering from C. glaucophylla was low but trunk/ground scattering from C. glaucophylla exceeded that from E. melanophloia.

At PHH, the backscatter is dominated by the trunk/ground term with a small contribution from the branch/ground mechanism. Foliage and trunk/ground backscatter are near equally responsible for the PVV total backscatter, while the HV contribution is attributed totally to the foliage. Branch/ground scattering from E. melanophloia and C. glaucophylla, was approximately equal.

Despite having an FPC of only 16%, the total C-band at all polarisations is still strong. It is important to note that CHV backscatter is equal to that of 111\_12 and is the strongest recorded for all simulated plots. It is observed that both these plots consist of the C. glaucophylla - E. melanophloia association, whereby both species maintain the same crown height (i.e., no emergents). As a result, the SAR signal penetrates the open canopy and is volume scattered by the foliage and small branches, from both species, within the same canopy area.

# 12.4.3 Mixed Eucalyptus woodlands

Both 142\_18 and 58\_29 represented woodlands, which were dominated solely by Eucalypt species. Given the similarities between these SSUs (i.e., both consisting entirely of decurrent species with an understorey), there is exist large differences between the magnitude of the total CVV and PHV backscatter for these simulated woodlands. 58\_29 records the strongest total CVV backscatter (-4.73 dB) of all the simulated Secondary Sampling Units, while 142\_18 is responsible for the weakest (-23.26 dB). This may be explained by the significant ground response at CVV for 58\_29, since both plots have similar backscatter from the foliage. The PHV backscatter for 58\_29 is approximately double the magnitude of that recorded for 142\_18.

Both these SSUs record single-bounce ground backscatter which is stronger than any of the other simulated plots.

<u>142\_18</u> The woodlands represented by 142\_18 were relatively open and comprised entirely of E. populnea although E. mitchelli sometimes occurred in the understorey. The foliage is the dominant contributor to all polarised backscatter at C-band. HH and VV backscatter is of equal magnitude and considerably stronger than HV.

At L-band, trunk/ground interaction contributed significantly, particularly at HH polarisations, which was attributed to the openness of the canopy. Branch/ground interactions also contributed at this polarisation. Backscatter at LVV is weaker than at LHH and is dominated by foliage and trunk/ground interaction. At both C- and L-band, HV backscatter is weak and totally attributed to the foliage term.

At P-band, the backscatter at all polarisations is dominated by the trunk/ground interaction and is strongest at HH polarisation. The branch/

ground interaction was insignificant which could be attributable to the lack of large branches in this relative low (~ 50 Mg ha<sup>-1</sup>) biomass woodland.

58\_29 A mix of E. populnea and E. melanophloia was evident within 58\_29, where an understorey dominated by E. melanophloia also occurred.

This plot is responsible for the strongest contribution at C-band from the ground scattering term. For CHH, the foliage contribution is only slightly greater than that of the ground. However, for CVV (which demonstrates the strongest VV backscatter at C-band of all simulated plots), there is equal contribution from the foliage and ground terms. The foliage dominates the HV backscatter at all frequencies. This is evidence that for those low biomass woodland communities, dominated by eucalypts, there is a significant contribution to the backscatter from the ground.

Furthermore, there exists a considerably more even contribution from all scattering terms, which is not evident in the other simulated SSUs. At L-band, the HH backscatter is dominated by the trunk/ground term; however, the branch/foliage and ground are also significant contributors. The VV polarisation is dominated by the ground term; however, the branch/foliage and trunk/ground term also contribute to the total LVV backscatter. At L-band, trunk/ground scattering was particularly evident from E. populnea, which was greater in number (45 compared to 19 E. melanophloia). Branch/ground scattering from both species was generally similar.

For P-band, contributing interactions to the HH backscatter are similar to that for L-band. The only difference is that the branch/ground term dominates instead of the single bounce ground interaction. The VV backscatter at P-band is largely attributed to the foliage, trunk/ground and ground terms, which are responsible for backscatter of equal magnitude. At P-band, branch/ground and also trunk/ground scattering was of similar magnitude from both E. populnea and E. melanophloia (the latter supported larger individuals).

This SSU contains no excurrent species. Consequently, the lack of preferential horizontal branching may explain the magnitude of the ground response, which is stronger than all other simulated SSUs. Horizontal branching is more effective in the attenuation of the backscattered signal (either from the ground or trunk/ground interaction) than alternatively orientated scatterers, such as those present in the decurrent species (i.e., E. populnea).

12.5 Relationship between scattering mechanisms and biomass components The contributions of the different scattering mechanisms and their relationships with the biomass of the various components (i.e., leaf and small branch, large branch and total) were investigated for both excurrent and decurrent forms. This analysis is instrumental for investigating the interrelationships between the biomass components and their subsequent impact on the relationships established between SAR data and above ground biomass components.

The collective responses of these different woodland types in terms of the contribution of the four scattering terms to the total backscatter are demonstrated in Appendix F.

# 12.5.1 Foliage and Small Branch Biomass

For both excurrent and decurrent species, C-band backscatter was dominated by volume scattering from the foliage and small branch biomass at HH and VV polarisations. However, the strongest relationship was observed with the CHV backscatter (Figure 12.3), which is almost entirely attributed to volume scattering through branch/foliage interactions. The backscatter increased from -25 dB to -16 dB for C. glaucophylla (biomass < 8 Mg ha-1) and -32 dB to -18 dB for E. populnea, *E. melanophloia* and A. leiocarpa (Biomass < 4 Mg ha-1).



Figure 12.3 Relationships between C-band HV backscatter and leaf and small (<1cm) branch biomass for excurrent and decurrent forms

In addition to C-band, it was observed that the decurrent species also demonstrate a significant backscatter contribution from the branch/foliage term at L- and P-band. Relationships between LHV and the small branch biomass were evident and attributed to an inherent relationship with large branch biomass. This contrasts with the coniferous species, which have a dominant contribution from the branch/foliage, only at C-band.

The ground response also was a dominant contributor to the backscatter from the foliage, for the co-polarised data at C-band, for both species type.

### 12.5.2 Large Branch Biomass

For the coniferous species, there is a change in the dominant scattering term from the branch/foliage to the trunk/ground as the wavelength increases. A general increase in C-band HH and VV backscatter and large (> 1-  $\sim$ 10 cm) branches was observed for C. glaucophylla, which was attributed to the strong inherent relationships between the small and large branch biomass for this species. All backscatter at C-band and L-band VV and HV, is dominated by the branch/foliage term. However, this contrasts strongly with the backscatter at LHH and all polarisations at P-band, which is dominated singularly by the trunk/ground term.

At LHH, the wavelength is long enough to be scattered by the trunk/ground term, which dominates the total backscatter. As a function of the HH polarisation, the backscatter is not attenuated by the preferential horizontal branching. This is not the case for the VV backscatter which tends to be attenuated by the horizontal branching and as a result, the branch/foliage dominates and co-dominates the total backscatter. Relationships observed between LHH backscatter and large branch biomass for both excurrent and decurrent forms can be attributed to an inherent relationship with the biomass of the trunks, since minimal interaction with the branch layer was suggested.

With respect to the decurrent form, no increase in C-band branch/ground and trunk/ground contributions with large branch biomass was evident. The backscatter from the large branch biomass is dominated by the branch/foliage term at HV polarisation for all wavelengths. This is also true for the co-polarised backscatter at C-band. The HH and VV backscatter from the longer wavelengths is dominated by the trunk/ground term. However, at LVV and PVV, the total backscatter is a cumulative function of all scattering terms.

# 12.5.3 Trunk Biomass

For C. glaucophylla, L-band HH backscatter was almost exclusively associated with trunk/ground scattering. However, for the decurrent species (E. populnea, E. melanophloia, A. leiocarpa), the overall return is a function of both trunk/ground interactions and branch/ground interactions. As the trunk biomass increases, a corresponding increase in LHH trunk/ground backscatter is observed, particularly where trunk biomass exceeded 20 Mg ha<sup>-1</sup>. In contrast, for the decurrent species, there is an increase from -20 db to -10dB, corresponding with an increase in trunk biomass of 10-30 Mg ha<sup>-1</sup>. Above this

range, the SAR backscatter appeared less sensitive to increases in trunk biomass.

At L-band VV, the backscatter is a cumulative function of contributions from the ground, branch layer and trunk/ground scattering mechanisms. Consequently, no trends with the biomass of specific components were observed. However, C. glaucophylla demonstrated an increase in the overall LVV return with aboveground biomass, in which volume scattering from the branches was responsible for the greatest contribution.

At L-band HV, a strong relationship with trunk biomass was observed for C. glaucophylla. This is largely attributed to an inherent relationship with the large branch biomass. In contrast, LHV backscatter from the decurrent species increased with large branch biomass, as a function of its interaction with that component.

A strong relationship was observed between the P-band HH backscatter and the trunk and large branch biomass for C. glaucophylla (Figure 12.4a), although the interaction was primarily with the trunks. This was also evident at PVV; however, ground contributions were more significant. PHV backscatter was primarily associated with trunk/ground interactions although volume and branch/ground contributions increased steadily with the biomass of both the trunks and large branches. For the decurrent species (i.e., E. populnea, E. melanophloia, A. leiocarpa; Fig 12.4b), P-band HH returns were primarily due to the trunk/ground mechanism, with the branch/ground term also being significant.



Figure 12.4 Relationship between L-band and P-band backscatter and both trunk and large branch biomass for a) excurrent and b) decurrent forms

### 12.5.4 Total Biomass

For both excurrent and decurrent species, LHH backscatter is dominated by the trunk/ground term. These LHH returns through trunk/ground scattering would be closely related to above-ground biomass; since scattering through this mechanism dominates the overall return and an inherent and close relationship exists between the biomass of trunks and that of affiliated components. However, this relationship will differ according to excurrent and decurrent forms.

### 12.6 Summary

The model of Durden et al. (1989) provided simulations of the SAR backscatter from 9 of the Secondary Sampling Units, containing associations of excurrent and decurrent species. After classifying the excurrent and decurrent species according to eucalypt and coniferous species, the backscatter was also simulated according to total and component biomass. In terms of wavelength, no significant difference existed between the actual and simulated backscatter for C-band VV and HV, and the co polarised backscatter recorded at L- and Pband. Significant differences were observed for CHH, LHV and PHV backscatter. This resulted in the underestimation of the backscatter. An overview of the scattering mechanisms according to wavelength is provided below.

At C-band, the co-polarised backscatter was largely a function of volume scattering from the foliage and small branches. It also demonstrated a greater sensitivity than the longer wavelengths to the ground surface. This is due to the influence of the decurrent growth form, which demonstrates considerably stronger backscatter at C-band than the excurrent species. This result is supported by Wang et al. (1998), whose investigation of Loblolly Pines found that the co-polarised backscatter at the longer wavelengths is more sensitive to the surface than C-band. The HV backscatter at C-band was entirely due to volume scattering from the foliage and small branches. The HV response was

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lower for those woodlands dominated by decurrent species, which can be attributed to the sparse distribution of leaves within the canopy.

For L-band at HH polarisation, the trunk/ground double bounce response was the greatest contributor to the backscatter. Correspondingly, the remaining scattering mechanisms demonstrate a reduced contribution, particularly in the higher biomass woodlands, dominated by C. glaucophylla. The VV backscatter at L-band is dominated by volume scattering from the canopy of all woodlands. The trunk/ground term is also significant from those woodlands with a high proportion of E. melanophloia and E. populnea. The HV backscatter at L-band is dominated by contributions through volume scattering from the upper branch layer.

At P-band, the HH polarised backscatter was dominated by the trunk/ground term, while at VV polarisation, the contributions from the ground, branch/ground and volume scattering were greater and also variable. This suggests selective interaction with different components depending on size and dimensions. At HV polarisation, volume and branch/ground scattering dominated the backscatter from those SSUs dominated by decurrent species. Trunk/ground scattering was more prevalent in C. glaucophylla dominated woodlands, particularly those of higher biomass.

In terms of relationships between the scattering mechanisms and biomass components, both excurrent and decurrent forms demonstrated a dominance of volume scattering from the foliage and small branch biomass at C-band. However, when considering the larger biomass components (e.g., trunk, large branch biomass), differences between the excurrent and decurrent species became more apparent. These differences and the inherent relationships between biomass components are discussed further in Chapter 13. Further simulations for different combinations of stands have been undertaken using the model of Durden et al. (1989), largely to support the development of SAR inversion models (Moghaddam and Lucas 2003). However, the reporting of these is beyond the scope of the thesis.

# Chapter 13

# Discussion

#### 13.1 Overview

Through this research, arguably the most comprehensive remote sensing dataset relating to subtropical woodlands has been acquired in Australia. Furthermore, the data were collected at a time where rates of vegetation clearance were at a maximum in Queensland and the data therefore represents a major resource with which to quantify future biomass losses through further clearing and to observe the impacts of prior clearance activity and management on the recovery of these woodlands, particular when and if abandonment occurs.

This discussion is divided into three sections. Section 13.2 considers how the previous management and use of the land has resulted in the composition of species and communities, the structural diversity and biomass levels, as observed using the remote sensing data acquired in 2000. The different structural types and the allocation of biomass are also reviewed, as this knowledge is considered fundamental to understanding how and why SAR backscatter varies within and between woodland types.

Section 13.3 establishes the relative importance of key parameters (namely frequency, polarization and incidence angle) that impact on the SAR return from the woodlands. The saturation of the SAR return will then be discussed in detail, as the rate of increase in SAR backscatter to the level of saturation is, in contrast to denser, more closed forests, relatively similar for C-band HV, L-band and P-band.

In this context, relationships between FPC and biomass will be explored further and the additional benefits of integrating optical data presented. The interaction of microwaves of different frequency and polarization with different components of the vegetation, as established through SAR simulation modeling, is also reviewed. Options for mapping biomass are proposed and the concept of SAR inversion is introduced.

Section 13.4 focuses on the potential future use of data from spaceborne sensors including the historical JERS-1 SAR and ERS-1/2 SAR, the current ENVISAT ASAR and RADARSAT SAR and the proposed ALOS PALSAR. The benefits of integrating data from optical satellite sensors are also highlighted.

#### 13.2 Woodland species/community composition, structure and biomass

Throughout the late 1990s and 2000, vegetation clearance (particularly in Queensland) was extensive, attracting the attention of both State and Federal governments and the international community. However, many of the woodlands cleared, and also those that remained intact, had already been impacted by anthropogenic activities (e.g., commercial harvesting and grazing) and natural events (e.g., fire) over the previous decades. These past impacts were manifested in the biomass and structure of the different woodland communities, as observed using the remote sensing data acquired over the Injune study area in 2000.

This has study raised two important issues. First, different woodland communities were associated with different categories of biomass and second, the structure of the woodland was very complex due to the occurrence, in varying proportions, of both decurrent and excurrent forms. These observations are significant, as both the magnitudes of the biomass (including allocation to different components) and the structure of the woodlands were determined as being important influences on
the SAR response. It is important to remember that the species composition and the distribution of structure and biomass are discussed in terms of the lidarderived biomass. The discussion is not, therefore, restricted to the composition of the 34 SSUs.

#### 13.2.1 Why does the biomass vary by community?

Within the study area, approximately 50 % of the woodlands supported a biomass above the mean of 86 Mg ha<sup>-1</sup> with over 84 % of the woodlands supporting a biomass above 50 Mg ha<sup>-1</sup>. Approximately 10% of the area sampled within the 4500 SSUs was non-vegetated (i.e., cleared). This reflects the dominance of clearing within the study area and suggests that few types of woodland are regenerating.

An association between the composition of the woodland communities and the levels of biomass also emerged. Most of the higher (>100 Mg ha<sup>-1</sup>) biomass woodlands contained a greater proportion of *C. glaucophylla, A. leiocarpa* and *E. melanophloia* within the community. At these biomass levels, the canopies of *C. glaucophylla* and *E. melanophloia* were often sufficiently closed for these to enter the forest category (defined as 51-80 % crown cover which approximates to 30-70 % FPC). The more open woodlands of higher biomass often contain larger Eucalyptus and Angophora species, with *A. leiocarpa* and *E. dealbata* being particularly prominent. Woodlands of intermediate (50-100 Mg ha<sup>-1</sup>) biomass included those dominated by *C. glaucophylla* and *A. leiocarpa* but also by *E. melanophloia, E. populnea* and other Eucalyptus species. Lower (< 50 Mg ha<sup>-1</sup>) biomass woodlands were characterized typically by *A. harpophylla* regrowth but also included sparser stands of *Acacia spp., E. mitchelli* and also *C. glaucophylla* and *E. melanophloia*.

The different levels of biomass observed and their associations with different species compositions are attributable, in part, to the past history of vegetation management in the region. Woodlands at the lower end of the biomass range occur largely as a result of regeneration (e.g., following clearing or fire events) or selective removal of trees (e.g., ring barking). In both cases, the biomass may be similar whilst the woodlands may be structurally distinct. As an example, woodland with a few sparsely distributed *E. populnea*, may support a biomass similar to regenerating *A. harpophylla* as the biomass of a few single-stemmed *E. populnea* individuals may equate to the biomass of several hundred small *A. harpophylla* shrubs with multiple stems. Extensive areas of both woodland types occur but have been difficult to quantify. For example, the sparseness of *E. populnea* canopies and also the low FPC of *A. harpophylla* regrowth often limit their detection using optical sensor data and, although the FPC of *A. harpophylla* may be high, confusion with higher biomass woodlands occurs. For these reasons, the extensive areas of *A. harpophylla* regrowth have been difficult to quantify (QLDDNRM 2003).

The majority (~84 %) of woodlands support a biomass greater than 50 Mg ha<sup>-1</sup>, which can be attributed to the extensive clearance of remnant but also some nonremnant and regenerating vegetation throughout the area (QLDDNRM 2003). The Queensland Herbarium consider that vegetation is not remnant if it is less than 70 % of height or 50 % of cover of the dominant stratum, relative to the normal height and cover of the stratum (Boulter *et al.* 2000). A comparison of clearing rates in woody vegetation over the 1995-2000 period suggested that of all the woody vegetation cleared, approximately half was non-remnant in each year (QLDDNRM 2003). The greater proportion of clearing was also of woodlands with an FPC of 24 % for 1995-1997, 29 % for 1997-1999 and 23 % for 1999-2001 (although areas of young regrowth were not considered in these estimates). In terms of basal area, the greatest frequency of clearing occurred in woodlands with 9 m<sup>2</sup> ha<sup>-1</sup> between 1991-95, 10 m<sup>2</sup> ha<sup>-1</sup> for 1995-97, 11 m<sup>2</sup> ha<sup>-1</sup> for 1997-1999 and 8.4 m<sup>2</sup> ha<sup>-1</sup> for 1999-2001. In other words, the majority of woodlands cleared were of relatively low cover and biomass, with an FPC of 30 % corresponding to a biomass of approximately 50-60 Mg ha<sup>-1</sup>. This, in part, accounts for the relative scarcity of these low biomass woodlands in the study area. In this assessment, it was recognized that the clearance figures are representative of Queensland as a whole and are more indicative of the events occurring in the Injune area.

At the higher (> 100 Mg ha<sup>-1</sup>) end of the biomass range, large individuals of the species A. leiocarpa were commonplace with many individuals having survived due to their very low commercial value. When several large individuals occurred together, these trees contributed collectively to produce a high biomass. Other woodland communities achieving high biomass levels were those dominated by C. glaucophylla, many of which were mixed with E. melanophloia. These high levels of biomass occur partly because C. glaucophylla is exploited commercially and hence the woodlands are managed actively for timber production (largely for building materials such as house framing and flooring). Most woodland areas are managed sustainably with harvesting occurring, on average, every 30 years during which mature, diseased, damaged or crowded trees are selectively removed. Furthermore, fire management practices have favored the predominance of C. glaucophylla in many areas of woodland. A number of other species (e.g., L. angustifolius) have also been utilized in the past (e.g., for fence posts and railway sleepers) and large individuals (although occurring) are rare.

The differential fertility of soils can make a large difference to the growth and hence the allocation of biomass (as indicated in Chapter 5). At Injune, both clay and sand are commonplace. The fertility of these soils varies, with species being more confined to sandy or sandy clay loams. As an example, *C. glaucophylla* is

prevalent and most vigorous in deep sandy soils adjacent to creeks where it is often the only occupant, although can occur in shallower sandy and light clay soils. On shallow sands over clay, *C. glaucophylla* may be associated within other species (e.g., *E. crebra*). The soil therefore plays a key role in biomass distribution and allocation across the landscape.

The land management practices further impact on the composition of the woodlands and hence the biomass. For example, active grazing impacts on the ability of tree species to regenerate and survive. Many State Forests with C. glaucophylla, for example, are leased for grazing. Grass production is also promoted in some woodland through removal (e.g., felling, poisoning or ring barking) of individual trees of selected species (e.g., E. populnea). Management practices also influence the state of the understorey. In locked-up stands of regenerating C. *glaucophylla*, for example, selective thinning is frequently undertaken to encourage regrowth. Vegetation thickening is also commonplace throughout the area and attributable to changing management practices but also fire regimes. As a result, relatively dense understoreys are frequent, although approximately 35 % of woodlands did not support an established understorey. Fire also impacts substantially on the woodlands with young C. glaucophylla being particularly susceptible and mature individuals of this species are often damaged. Fire management systems have therefore encouraged the survival and spread of C. glaucophylla and dominance of this species in the upper canopy. These practices and events collectively lead to removal of trees of different height and diameter classes and impact on the vertical distribution of biomass.

#### 13.2.2 Why do different structural types occur?

The variation in structural types, from decurrent to excurrent, is typical of many types of woodland where the biogeographic distribution of coniferous species (e.g.,

*C. glaucophylla*) overlaps with species such as the Eucalyptus, Acacias or Angophoras. Within the decurrent growth form, the proportion of biomass allocated to the trunk and branches is often similar. However, excurrent forms allocate the majority (often > 80 %) of biomass to the trunks. Pure stands of excurrent and decurrent forms do exist, but many types of woodland contain some Callitris species and therefore woodlands supporting a mixture of forms are commonplace.

At Injune, the majority of tree species were of the decurrent form with differences within this form attributable largely to the differential levels of biomass accumulated and the subsequent proportions allocated to the various components. Most tree species of this form (e.g., *E. populnea*, *E. melanophloia*) were of relatively low biomass with between 30 and 40 % of the biomass allocated to the branches and the biomass of most woodlands dominated by these species rarely exceeded 100 Mg ha-1. In contrast, A. leiocarpa allocated a greater amount of biomass to the branches and also the total biomass was generally greater in magnitude. C. *glaucophylla* was native to the Injune study site. Its natural growth was encouraged due to its commercial value, although plantations were rare. Pure stands of this excurrent form were uncommon and, as C. glaucophylla was frequent throughout the areas, woodlands supporting a mixture of forms were typical. Species such as A. harpophylla and E. mitchelli were also structurally different from the excurrent and decurrent species, as these allocated a significant proportion of the biomass to the leaves, particularly during the early stages of regrowth and were typically multiple stemmed.

Within these woodlands, competition between species and individuals was a major determinant of the composition and structure of the woodlands. Many trees are restricted in their ability to grow due to overcrowding. Locked up stands of *C. glaucophylla,* represent a good example of overcrowding.

The combination of both excurrent and decurrent growth forms at different stages of regeneration and degradation and affected by crowding, complicated the interpretation of the SAR response from these woodlands, particularly as a diversity of structures occurs and pure stands of similar aged individuals are rare. Even so, recognizing this complexity was fundamental in the evaluation of SAR data for quantifying the biomass, structure and species/community composition of these woodlands.

#### 13.2.3 Relationships between biomass, structure and FPC

An important observation was that, in many stands, the total above ground biomass increased in proportion to FPC. The only exception was stands with a high proportion of *A. leiocarpa*. This increase was also reflected through the proportional relationship between leaf and woody (i.e., trunk and branch) biomass.

To explain this relationship, an understanding of the growth strategies of woodland is required. In Chapter 9, relationships established between different structural components indicated that during the early stages of growth, the height of the trees increased in proportion to the diameter. However, the increase in height for most species (particularly of the excurrent form) became asymptotic and, instead, crown area tended to increase in proportion to the diameter. For these reasons, an increase in leaf cover (i.e., FPC) in proportion to the woody biomass was evident in many stands. This is in contrast to many closed-forests in temperate or tropical regions where a closed canopy rapidly forms in the early stages of regeneration and the rate of increase in canopy cover rapidly becomes asymptotic. Regenerating tropical forests, for example, can attain a Leaf Area Index

(LAI) that is equivalent to their mature counterparts in less than 10 years (Lucas *et al.* 1996). In this case, and in contrast to open woodlands, neither canopy cover nor leaf biomass increase in direct proportion to the woody biomass. A similar scenario occurs in temperate plantations. In open woodlands, the reverse can also occur when losses of biomass (e.g., through selective removal of trees) results in a corresponding decrease in the FPC. These concepts are illustrated in Figure 13.1.

Woodlands with a high proportion of *A. leiocarpa* are an exception as increases in biomass at the higher level are not associated with increases in FPC. This may be reflective of a) the predominantly vertical orientation of leaves associated with these species, b) the lack of an understorey under many large *A. leiocarpa* individuals and c) the hollowing of the canopy of larger trees. Many large *A. leiocarpa* trees often have few leaves at the center, with these occurring largely on the periphery of the crown.

In summary, the study has demonstrated that approximately 50 % of woodlands at Injune support a biomass of > 86 Mg ha<sup>-1</sup> with most having a biomass of > 50 Mg ha<sup>-1</sup>.

The distribution of biomass is linked closely to the species composition of the woodland communities and past and present anthropogenic activity and natural disturbance have had a significant impact on the distribution. The woodlands are also structurally complex as stands occur at various stages of regeneration and degradation and contain a mix of both decurrent (e.g., eucalypts, angophoras) and excurrent (e.g., pines) growth forms. In contrast to many closed-forest environments, a close relationship between FPC (which rarely exceeds 50 %) and biomass exists within open woodland environments. All of the factors will

influence the SAR return from these woodlands and also the ability to retrieve biomass and structural attributes and differentiate woodland communities.



Figure 13.1 Diagrammatic representations of changes in canopy cover and woody biomass for a) a tropical regenerating forest or temperate coniferous plantation, b) a regenerating open woodland with expanding crowns during the latter stages and c) an open woodland where tree loss occurs through, for example, ring barking or dieback.

#### 13.3 SAR returns from woodlands

The study has demonstrated the relationships between biomass and structure with SAR backscatter at different frequencies and polarizations and also the importance of incidence angle. Key observations are that the SAR backscatter increases with biomass to an asymptote at all frequencies and polarizations. The levels at which the relationship between C-band HV, L-band and P-band SAR backscatter and biomass saturate and the rate of increase in SAR backscatter to the level of saturation were similar. These observations are in contrast to observations from closed-forests where levels of saturation were better separated and the rate of SAR backscatter increase with biomass (at higher frequencies) was faster (Dobson *et al.* 1992, Moghaddam *et al.* 1994, Ranson and Sun 1994, Rauste *et al.* 1994, Imhoff, 1995b). The benefits of integrating FPC with SAR backscatter data, particularly for discriminating woody and non-woody regrowth and also certain woodland communities has been highlighted. Differential interaction of microwaves with canopy components has been established through SAR backscatter modeling. These outcomes are discussed below.

#### **13.3.1 Empirical Relationships**

A number of approaches to establishing quantitative relationships between SAR backscatter and biomass have been considered. In several cases (e.g., Luckman *et al.* 1997b), logarithmic relationships have been applied. The polynomial function has also been used to describe the relationship between SAR backscatter and biomass for boreal forest (Rignot *et al.* 1994) and tropical rainforest (Santos *et al.* 2003). In this study, however, a function based on chi-square minimization was used and was considered to provide the best and most consistent fit to the relationship between SAR backscatter and biomass. This approach allowed the SAR backscatter at different incidence angles to be compared and the saturation levels to be determined quantitatively.

#### 13.3.2 Influence of incidence angle.

The study has demonstrated that incidence angle is a major influence on the relationship between SAR backscatter and biomass but also a hindrance to the mapping of biomass from airborne SAR. An advantage of using spaceborne SAR is that these incidence angle variations are largely overcome. The study has highlighted the importance of acquiring data at a higher incidence angle, since the dynamic range of the backscatter data tends to be greater for the open woodland situation. Scatter within the relationship is also reduced at the higher incidence angles. However, these observations may be specific to the open woodland situation as they contrast with those focusing on dense, closed forests (e.g., Moghaddam et al. 1994) which have shown a stronger relationship with SAR backscatter at lower incidence angles. Specifically, surface scattering was found to increase and volume scattering decrease as the incidence angle decreased and approached nadir. At these lower angles, the SAR wave was considered to have a greater likelihood of directly reaching the forest floor and subsequently interacting with the biomass of the tree. A plausible reason for these differences is that the open nature of the canopy does not lead to the same attenuation of microwaves by the foliage as in closed forests. Therefore a greater proportion reaches the ground and is then able to be scattered directly back to the sensor (e.g., single bounce) or from tree trunks (i.e., double bounce). .

#### 13.3.3 Saturation of Biomass

As is typical of most studies, saturation of the SAR return was observed at all frequencies and polarizations, with the level of saturation being greater at lower frequencies. Saturation of the SAR backscatter, however, occurred at higher levels of biomass for HV compared to co-polarised data. This was particularly evident for C-band HV and P-band HV data. Variations in the saturation of the SAR return with incidence angle were observed, although no patterns were evident.

However, Moghaddam *et al.* (1994) suggested that, for closed forests, saturation takes place at larger biomass values for smaller incidence angles (e.g., an incidence angle of 35° and 50° resulted in the saturation of biomass at 300 Mg ha<sup>-1</sup> and 150 Mg ha<sup>-1</sup> respectively). This situation is likely to differ for the more open canopies, as outlined above.

The relatively low level of biomass at which saturation occurs suggests that SAR might be limited for estimating the biomass of woodlands > 100 Mg ha<sup>-1</sup>. This represents a major limitation to the use of SAR but one which might be overcome through the use of SAR inversion models which consider the differential interaction of microwaves with different components of the woodland canopy. Such models are discussed briefly later in this chapter.

#### 13.3.4 Influence of FPC

The relative similarity in the level of saturation between C-band HV, L-band and P-band was attributed partly to the observed relationship between FPC and woody biomass. In closed forest situations (e.g., coniferous plantations), where many studies have focused, the rapid formation of a complete canopy leads to saturation of the C band signal at a biomass approximating 20-30 Mg ha<sup>-1</sup>. This relatively low level of saturation is attributable to the large quantities of leaves and small branches preventing penetration of microwaves into the canopy and causing depolarization of the SAR signal through volume scattering. In open woodlands, depolarization by the canopy still occurs (as confirmed through the simulations) but appears to do so in proportion to canopy cover, as indicated through the relationships with FPC. The SAR backscatter modeling also suggested that C-band HV interactions were entirely with the foliage and small branches contained within the canopy. For these reasons, the saturation of the SAR return does not occur until a certain FPC has been attained which equates approximately to a biomass of

at least 60-70 Mg ha<sup>-1</sup>. As FPC increased in proportion to the woody biomass in most stands, the levels of saturation and the rate of SAR backscatter increase with biomass at L-band and P-band can therefore be expected to be similar to that observed at C-band HV.

#### 13.3.5 Simulation of backscatter at Injune

The simulation of the SAR returns from selected woodland structures was considered essential given that relationships between SAR backscatter and leaf, branch and trunk biomass were complicated by the inherent relationships between the biomass of these components. By carefully parameterising the model of Durden *et al.* (1989) for a mixture of woodland structures, a better understanding of microwave interaction was obtained. The parameterization was undertaken based on representative trees, using a full range of measurements and ensuring the biomass of the simulated SSUs was equivalent to the biomass of the SSU, as estimated by applying allometric equations to all trees. Although the model provided a good indication of the SAR return and the scattering mechanisms involved, it was recognized that the woodlands simulated were simplified versions of a more complex structure and the likelihood of obtaining a good simulation was reduced as more structures were introduced, particularly as the interaction between structures was not considered.

The modeling provided a unique insight into frequencies and polarizations that might provide the retrieval of specific structural and biomass attributes. Specifically, C-band HV backscatter was shown to be exclusively with the foliage and small branches and showed a steady increase with the biomass of these components. L-band HH interaction was primarily with the trunks and, in the case of excurrent forms, a reasonable estimate of trunk and also above ground biomass may be achieved, particularly as the leaves and branches collectively represent a smaller proportion of the biomass. L-band HH interaction with the trunks of decurrent forms also occurred but the retrieval of total biomass is complicated because of the enormous variability in the relationships between trunk and branch biomass. The retrieval of trunk and also total biomass is also compromised when a mix of excurrent and decurrent forms occurs, as in the case of many of these woodlands. L-band HV returns demonstrate a good relationship with large branch biomass of both excurrent and decurrent forms and interaction is almost exclusively with the crown layer. At P-band, strong interactions with the trunks are particularly evident at HH polarizations and some ground and also volume scattering from the branches was evident at P-band HV and VV respectively. However, considerable scatter in the relationships was observed for decurrent forms suggesting a more complex interaction compared to the higher frequencies. The simulation modeling suggested that there was near exclusive interaction between microwaves of certain frequencies and polarizations and the different components of the biomass. These observations also suggest that higher levels of biomass may be retrieved by SAR through consideration of these different interactions at different frequencies and polarizations.

#### **13.3.6** Integration of data from optical sensors.

From this research, several advantages of integrating data from optical sensors were highlighted. First, FPC estimated from Landsat sensor data using a combination of the NDVI and the Short Wave InfraRed (SWIR) channel, provides an indication of the presence or absence of vegetation. To a large extent, FPC can be used to estimate biomass with the exception of woodlands with a high proportion of species such as *A. leiocarpa*. Second, optical remote sensing data can provide information on the species/community composition of woodlands. However, a limitation of using Landsat sensor data is that the dynamic range and also spatial resolution of the data is generally insufficient to discriminate most

communities on the basis of spectral reflectance data alone, particularly in species rich and structurally diverse woodlands such as those at Injune. Even so, the community composition of woodlands can be discriminated to a certain extent using FPC although further studies are required to establish the reliability and consistency in the classification. The benefits of utilizing these data are expanded below.

#### 13.3.7 Importance of FPC

FPC is an important discriminator of vegetated and non-vegetated surfaces. FPC itself is defined as the amount of foliage cover as a proportion of the amount of other surfaces (including non vegetation). FPC estimates are very sensitive to even small amounts of leaf cover and hence areas of relatively open woodland and also young regeneration (e.g., *A. leiocarpa* regrowth) can be detected with a reasonable degree of confidence. FPC is also an important measure as an increase in proportion with biomass is evident. Therefore, to a certain extent, FPC can be used to estimate biomass directly, although this approach is not applicable to all woodland types (e.g., *A. harpophylla* regrowth and high biomass *A. leiocarpa* stands).

Through integration of FPC data with data from SAR sensors, the level of information extracted can be enhanced. Specifically, FPC tends to increase with C-band HV backscatter. This increase is logical as both FPC and C-band HV backscatter are both sensitive to the amount and density of foliage and also smaller branches, partly through the strong inherent relationship observed between the biomass of these components. Hence, these two differing sources of information can confirm the presence or absence of vegetation.

Integration of FPC data with data from SAR sensors observing at longer wavelengths (i.e., L and P band) allows discrimination of woodlands supporting a greater proportion of biomass in a large number of smaller branches or trunks (i.e., multiple stemmed individuals) from those containing biomass at similar levels but within larger trunks or branches. Within Injune, the integration of data from FPC and also L-band data allowed such discrimination of these two structural types. The mapping of "woody" and "non-woody" regrowth can therefore be achieved using a combination of C-band HV backscatter (or FPC) and L-band HH backscatter. Mapping these regrowth types is important for several reasons. First, because the widespread removal of vegetation occurred as a result of perception regarding restrictions on future land clearing, it is anticipated that the areas cleared may be so extensive that landholders will be unable to maintain these in pasture and hence regrowth will become commonplace. Second, if large areas of A. harpophylla and similarly structured were regenerating in 1990, they should be regarded as forest (i.e., 20 % vegetation cover and potential to attain heights of > 5 m) under the carbon accounting rules established through the Kyoto Protocol and subsequent amendments. For this reason, mapping of these regrowth areas, the biomass they contain and their rates of biomass increase will need to be considered. The use of L-band SAR will be important as such low biomass areas cannot be discriminated using FPC or even C-band data alone, particularly as the FPC of higher biomass woodlands is often similar.

The FPC data also play an important role in discriminating certain vegetation types. In particular, communities that include *C. glaucophylla* and *E. melanophloia* typically support a high FPC, which allows their discrimination from lower FPC communities such as those including *A. leiocarpa*. In both cases, similar levels of biomass may be supported. In this case, the response of these communities may be similar at L-band but different levels of FPC are supported. In some

communities (e.g., those with a high proportion of *Acacia spp*.), the FPC may be high but the lower levels of biomass associated typically with these woodlands will be reflected in the reduced L-band and P-band SAR return.

#### 13.3.8 Species/community discrimination using optical sensor data

The discrimination of species and communities using Landsat sensor data appears to be limited. The woodland communities mapped using Aerial Photography Interpretation (API) to support the classification of Landsat sensor data were assumed to be similar within the polygons delineated. In practice, there was still considerable variability in the structures involved, which could not be adequately described from the Landsat data because of the relative coarse spatial resolution.

Discrimination of vegetation communities, however, is enhanced through the integration of FPC and SAR data. Even so, the discrimination of communities using SAR was limited as the variability in the dielectric and geometric properties of the vegetation was insufficient to allow discrimination based on these attributes alone.

To provide a more coherent description of woodland communities, the integration of CASI and laser data is essential, although such analyses were beyond the scope of this thesis. Nevertheless, such work is currently being undertaken in associated studies using a combination of CASI and laser but also HYMAP and Hyperion data. Using the available hyperspectral datasets, research into the characterization, discrimination and mapping of species/communities is continuing as the information can be used in conjunction with SAR data to provide a) improved habitat maps as information on both structure and biomass can be integrated and b) maps of species/community composition for improved accuracy in the estimation of structural attributes and the component biomass of woodlands through SAR inversion models.

#### 13.3.9 Approaches to mapping biomass

Several approaches to the integration of SAR data for the mapping of biomass can be considered. First, empirical relationships established between biomass and SAR backscatter at different wavelengths and polarizations can be used to map biomass. Significant variability in these relationships was observed at Injune and this was attributed largely to the diversity of vegetation structures and the variation in incidence angle. However, CTIC data could be used to map the biomass as incidence angle differences can, in part, be removed. An alternative approach would be to use cross-polarised data, which appear to show reduced sensitivity to incidence angle. However, if empirical relationships are used, the errors in the mapped estimates will be large, particularly when approaching or exceeding the level of saturation. The combination of SAR data and FPC data can, however, play a key role in the mapping of areas of regeneration. For example, areas of woody and non-woody regrowth can be mapped using FPC and C-band HV/L-band SAR. The higher biomass C. glaucophylla/E. melanophloia woodlands can also be distinguished from those dominated by A. leiocarpa due to differences in FPC. Such subtle differences could be used in, for example, rule-based classifications, to allow mapping of these communities and their associated biomass.

The mapping of biomass was not attempted as part of this work, largely because of the limitations outlined above. Also, the alternative approach of using SAR inversion modeling (Moghaddam and Lucas 2003) was considered to be a more viable option. In this approach, the SAR return is simulated at different frequencies and polarizations based on modeled inputs relating to key structural attributes (e.g., branch and trunk density) of the woodlands. A suite of polynomial curves relating the magnitude of the inputs to the SAR return can then be inverted to produce parameter maps (e.g., of crown density, dielectric constant and depth) from which biomass can be inferred. Preliminary results have been promising.

#### 13.4 Current and future spaceborne sensors

Based on the outcomes of this research, the potential benefits of using past, present and future space borne SAR and also optical/hyperspectral sensors can be evaluated. Key benefits include mapping of vegetation biomass categories (particularly below 100 Mg ha<sup>-1</sup>), discrimination of "woody" and "non-woody" regeneration and woodland structures, and the support of SAR inversion modeling. Table 13.1 outlines some of the main spaceborne SAR sensors that have, are or will be available.

For estimating biomass, the use of lower frequency sensors is necessary. Although no L-band sensors are currently operating, the Advanced Land Observing System (ALOS) Phase Arrayed L-band SAR (PALSAR) is due for launch in September 2004 and will be acquiring data in HH and HV polarizations over Australia in three consecutive years and at incidence angles of 34° and 43°. Based on observations on the influence of incidence angle, the 43° overpass is likely to be most appropriate for biomass estimation and the HV polarization is likely to provide the greater dynamic range.

Although C-band sensors will be less well placed for estimating biomass, the similarity with L-band (particularly in the case of C-band HV) in terms of the level of increase in backscatter with biomass, suggests that data from sensors such as the ENVISAT ASAR may be useful. However, in forests where the canopy is more closed, then the use of these data will be reduced. Even so, if these data are

integrated with FPC measurements, the closure of the canopy can be assessed and areas where the relationships are functional can be established. Otherwise, C-band data (particularly HV) will provide a similar role to FPC, in that they can be used to indicate canopy cover. Again, integration with L-band data will assist discrimination of "woody" and "non-woody" regeneration and mapping of woodland areas.

No space borne P-band data are available as yet and so their utility is limited beyond the use of airborne data. For inversion modeling, a combination of C and L-band data, perhaps with optical sensor data is critical. Discrimination of woodland communities to support the inversion may also be enhanced through the use of space borne hyperspectral (e.g., Hyperion data).

ble 13.1 Sensor	specifications o	of past	and current spa	iceborne SAR	sensors (Sourc	e: Adapted from	Bergen and Dobson 199
Sensor	Dates	Band /s	Polarisation/ s	Resolution (m)	Incidence Angle (°)	Image swath width (km)	Sampling Frequency (days)
US Space Shuttle	-						
SIR-C	April 1994, October 1994	C, L	Polarimetric	25	17-63	15-90	Daily over selected sites
X-SAR	April 1994, Oct 1994	×	VV	25	15-60	15-40	Daily over selected sites
<b>Existing Satellites</b>	-						
RADARSAT	1995-	С	HH	10-100	20-49 standard: 10	35-500	1-3 Wideswath, 24
					60 extended		Nepear
ERS-1	1991-	C	VV	30	23	100	35 Repeat
ERS-2	1995-	U,	VV	30	23 21	100 	35 Repeat
JEKS-1 Planned Satellites	1992-1998	Г	НН	18	¢£	G/	35 Kepeat
		,					
LightSAR	2002	L and	L-quad; X-VV or C-HH, HV	1-25, 100	TBD	100	1 Wideswath, 8-10 Repeat
		X					
RADARSAT-2	2001	С	HH, VV, HV	3-100	10-60	10-500	1-3 Wideswath, 24
FNWISAT/ASAR	1999	J	HH VV VH	30, 150, 1 km	15-45	IIn to 100 and	Repeat 3.35.168
		)				>400	
ALOS/PALSAR	2004	L	НН, НV	10-100	8-60	40-350	46
					standard; 18-43 scansar		
SRTM	2000	С, Х	VV	30	57	48	11

## Chapter 14

## **Conclusions and Recommendations**

#### 14.1 Overview

This study has provided a comprehensive evaluation of the potential of airborne polarimetric SAR for quantifying (and subsequently) mapping the biomass and structure of woodlands. This has been achieved using a combination of ground truth data, finer spatial resolution remote sensing data and SAR backscatter modelling. Through this latter process, a better understanding of the interaction of microwaves of different frequency and polarisation with different components of the vegetation canopy has been obtained.

The study has also outlined the benefits of integrating optical data. In particular, FPC data have provided the best opportunity for discriminating woodland communities, although integration with SAR data would assist their classification. Furthermore, by using FPC in conjunction with SAR data, a greater understanding of the interaction of microwaves with structures associated with different woodland types has been obtained. In particular, the strong relationship between FPC and biomass has been exposed which has led to a greater insight into woodland structure and dynamics and also a better understanding of the different saturation levels observed at C-band, L-band and P-band. The potential of using these combined datasets for differentiating communities (e.g., Acacia spp.) and also regeneration and degradation classes (e.g., those dominated by A. harpophylla) has also been illustrated. Using the current AIRSAR data, the limitations of saturation in estimating biomass have been further highlighted and the importance of incidence angle revealed. The benefits of integrating optical data in the classification of woodland structure, biomass and species/community composition have also been demonstrated. From this information, the potential benefits of using future spaceborne SAR sensors, namely the ENVISAT ASAR and ALOS PALSAR has been indicated. Specifically, the study recommends a combination of ALOS PALSAR and Landsat ETM+-derived FPC for deriving biomass class maps below 100 Mg ha<sup>-1</sup>, although consideration needs to be given to incidence angle effects. Based on this information, it is anticipated that better estimates of biomass will be obtained from ALOS PALSAR data acquired at a 43° rather than a 34° incidence angle. The use of ENVISAT ASAR and ALOS PALSAR with or without Landsat ETM+ data and a validated inversion algorithm is, however, recommended for quantifying higher biomass levels and for better interrogating the structure of the woodlands.

The research has also provided considerable insight into the woodland community composition, biomass and structure of the woodlands at Injune, a substantial integrated dataset for advancing remote sensing techniques (e.g., hyperspectral analysis, SAR inversion modelling) for better characterisation of the woodlands, and a strong base with which to conduct further studies. The following sections provide a more detailed list of the conclusions of the study.

## 14.2 Community composition, structure and biomass

• Analysis of the Aerial Photographic Interpretation (API) data for the 4500 Secondary Sampling Units revealed the enormous diversity of woodland structures near Injune which was attributed to the biogeographic distribution of species and the occurrence of a wide range of regeneration and degradation stages resulting from both natural events (e.g., fire and drought) and anthropogenic use (grazing) and

management (ring barking, poisoning, selective logging of locked up stands, grass cultivation).

- Despite the diversity of woodland associations, the species diversity was relatively low with C. glaucophylla, E. melanophloia, E. populnea and A. leiocarpa being particularly frequent.. Other notable species included Acacia spp., E. dealbata, E. decorticans and A. harpophylla. Subdominant or understorey species were absent from ~ 35 % of woodlands.
- A number of common structures were identified. Both decurrent (e.g., E. populnea, A. leiocarpa) and excurrent (C. glaucophylla) forms were commonplace, with many woodlands containing a mix of these forms. Regrowth forms (e.g., A. harpophylla, Acacia spp.), whereby a greater proportion of biomass was allocated to the leaves and a large number of small (~ < 5 cm) branches, were also frequent.</li>
- The mean biomass of the woodlands at Injune was 86 Mg ha<sup>-1</sup>, and the majority (85 %) supported a biomass ranging from 50 150 Mg ha<sup>-1</sup>. Due to extensive clearance in the area and the lack of regeneration, only ~ 10 % of the sampled area supported a biomass of < 20 Mg ha<sup>-1</sup>. The biomass distribution was linked closely to the species composition of the woodlands, with low biomass woodlands consisting largely of regrowth A. harpophylla, Acacia spp., E. mitchelli, E. melanophloia and C. glaucophylla. In the latter two cases, low biomass was associated also with degraded stands. At the higher end of the biomass range (> 150 Mg ha<sup>-1</sup>), A. leiocarpa and C. glaucophylla were commonplace. Woodlands with an intermediate biomass contained a mix of species, although some Eucalypt species were prevalent (e.g., E. populnea).

- Based on the analysis of the 34 sampled SSUs, woodlands dominated by excurrent forms allocated a greater proportion (as much as 90 %) of the biomass to the trunks. However, those with decurrent forms generally allocated < 50 % to the branches. Therefore, the trunks were a dominant biomass component in most woodland.</li>
- All woodlands supported a Foliage Projected Cover (FPC) of less than 60 %, confirming the openness of the canopy. Communities associated with a high FPC included C. glaucophylla and E. melanophloia and also Acacia spp. Those with low FPC included stands with a high proportion of A. leiocarpa, large individuals of which have expansive and often hollow crowns with vertically orientated leaves.
- Different species exhibited different growth strategies. In particular, many species (e.g., C. glaucophylla, E. melanophloia, E. populnea and A. leiocarpa) increased their height in proportion to diameter during the early stages. However, once a maximum height had been attained, expansion of many crowns occurred, resulting in a subsequent increase in crown area in proportion to diameter. For these reasons, a strong relationship between FPC and biomass (which also increases as a function of diameter) was observed. Such relationships would not be observed in tropical or temperate closed-canopy forests where canopy cover would not increase in proportion to biomass.

## 14.3 Allometric equations

- For many woodland species at Injune, allometric equations were already available and harvesting of E. populnea and E. melanophloia at Injune suggested that both leaf and branch biomass were reasonably well estimated using these equations. However, estimates of trunk and total above ground biomass deviated for both species at diameters > 40 cm. This variation was attributable to the different growth conditions and allocation of biomass at Dingo (where equations were originally derived) and Injune, which is several hundred kilometres distant.
- The new equations generated for C. glaucophylla significantly increased the accuracy of the biomass estimates at Injune, as a high correlation between biomass (total, component and subcomponent) and tree size measurements was obtained. Furthermore, by harvesting this species, dependence on unreliable surrogates (i.e., volume estimates based on taper equations) was avoided.
- The harvesting confirmed that the proportion of biomass allocated to the branches by E. populnea (> 50 %) was greater than that of E. melanophloia (40-50 %). However, considerable variation in the allocation of biomass to these components occurred, as demonstrated through the comparison of biomass data from both Dingo and Injune. C. glaucophylla allocated a greater proportion of biomass to the trunk and, in contrast to the other species, branches > 10 cm in diameter were uncommon.
- The data further indicated that the moisture content of both trunks and branches was higher in the upper extremities of the trees (e.g., branches < 4 cm) and decreased with height. Such information assisted calculation of the dielectric constant for these biomass components in the parameterisation of the forward simulation model.

- Harvesting of E. melanophloia, E. populnea and C. glaucophylla at Injune provided estimates of the subcomponent biomass (e.g., branches < 1 cm, 1-4 cm etc.). The resulting estimates suggested a strong correspondence between the biomass of branches < 1 cm and the leaves. Such information proved invaluable when parameterising the SAR simulation model.</li>
- Harvesting at the same time and location as the acquisition of the remote sensing data gave greater confidence in the subsequent estimates of biomass. A further benefit of harvesting was that data (e.g., moisture content, leaf biomass) specific to the time of remote sensing data acquisition, could be retrieved and used subsequently to support the simulation of the SAR backscatter from different structural components.
- Overall, reliability of estimates of biomass based on allometrics were reduced if the species measured in the plots were outside of the size range of those for which the equations were intended. E. mitchelli was the species with the greatest number of individuals outside of the biomass range. However, this species generally contributes only a small proportion of the biomass and further harvesting to increase the utility of the equation is probably not warranted. The biomass of large A. leiocarpa trees was also difficult to quantify due to the lack of allometric equations for this species, and additional harvesting of this species is recommended for refining the estimates of biomass.
- Strong relationships were established, for the main species (C. glaucophylla, E. melanophloia, E. populnea and A. leiocarpa, between different independent variables, including diameter at breast height (DBH), height (H) and crown area. Similarly, allometric equations for estimating the biomass of components from these variables were also

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generated. In undertaking this assessment, the capacity to spatially quantify the biomass of woodlands using estimates of tree height from lidar or crown area from lidar or CASI data has been provided.

- Allometric equations which related sapwood cross-sectional area of the stem to the biomass of the foliage for the dominant species, C. glaucophylla, E. melanophloia and E. populnea were also derived. The relationships for each of these species were very strong although such measures were deemed impractical for routine estimation of foliage biomass.
- 15.4 Empirical Relationships involving SAR backscatter
  - The relationship between total above-ground biomass and SAR backscatter was most appropriately described using a non-linear function that minimised the chi-squared statistic. This approach was considered superior to the use of logarithmic or polynomial functions and provided a comparison of relationships at differing incidence angles and a quantitative approach to determining levels of saturation.
  - Saturation of the SAR return varied with frequency and polarisation, with saturation occurring first at C-band, then L-band and P-band. The saturation was most similar (~ 60-75 Mg ha<sup>-1</sup>) between C-band HV and also L –band and P-band (particularly co-polarised). At all frequencies, the HV polarisation provided the greatest dynamic range and was considered to be most suited for biomass estimation.
  - The relationship between SAR backscatter and biomass varied with incidence angle, with the stronger relationships observed at incidence angles of ~ 57° - 60°. At this high incidence, the open nature of the woodland canopy facilitates specular reflectance from the ground surface, which is backscattered to the sensor, without being attenuated

by the canopy. Significant relationships were also obtained at angles approximately ~  $45^{\circ}$  -  $51^{\circ}$ , although were poorer at ~  $26^{\circ}$  -  $35^{\circ}$ .

- Generally, there was a large amount of scatter present in the relationship due to the diversity of species and structures. However, the stronger relationships were evident where more sparsely vegetated regions occurred and the incidence angle was higher.
- The relationship between FPC and SAR backscatter provided differentiation of the regrowth species (i.e., A. harpophylla) from the larger woodland species. This relationship was attributed to the corresponding increase in crown cover (resulting partly from crown expansion following attainment of maximum height) with biomass. Such a correspondence is not typically observed, for example, in tropical or temperate closed forest environments.
- The integration of FPC and SAR data can assist in the discrimination of early regenerating or low biomass woodlands (e.g., A. harpophylla regrowth, Acacia spp.), with high FPC and low biomass, from higher biomass woodlands, which also exhibit high FPC. A combination of FPC/C-band HV and also L or P band data can be used to map woody regrowth.

### 14.5 SAR backscatter modelling

Parameterisation of the forward simulation model of Durden et al. (1989) was undertaken with a view to better understand the interaction of microwaves with different structural components of the woodlands, identify the dominant scattering mechanisms and, ultimately, advance the development of SAR inversion models (Moghaddam and Lucas 2003). The parameterisation was undertaken using the measurements obtained through forest inventory and destructive harvesting together

with the allometric equations available for the species considered. Some homogenisation of the woodland structure was necessary, although the parameterisation ensured that the biomass of the different components was equivalent in the simulated and actual stands. In contrast to many previous studies, more than one species was modelled thereby allowing stands of varying structure to be considered.

- No significant difference existed between the actual and simulated backscatter for C-band VV and HV, and the co polarised backscatter recorded at L- and P-band. Significant differences were observed for CHH, LHV and PHV backscatter. This resulted in the underestimation of the backscatter. Discrepancies were attributed to mis-registration of the AIRSAR data, errors in data calibration and the ability to only parameterise the model for a few structural types.
- The branch/foliage response dominates the C-band backscatter at all polarisations, from the total and component biomass (trunk, large branch, small branch and foliage) for both the eucalypt and coniferous species. C-band HV microwaves were found to interact almost exclusively with the foliage and small branches. This exclusive interaction largely explains the strong relationship between FPC and C-band HV backscatter. Furthermore, the continued increase in FPC with SAR backscatter at most frequencies and polarisations together with field based observations suggests that FPC is related closely to above ground biomass. Such a relationship is likely to be specific to the open woodland environment.
- L- and P-band backscatter (particularly HH) from the trunk biomass is singularly dominated by the trunk-ground response for the coniferous species. However, this contrasts with the backscatter from the trunk

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biomass of the eucalypt species, which is a cumulative function of all the scattering components. Again, this is attributed to the open nature of the eucalypt canopy.

• The simulations confirmed that no single frequency or polarisation is optimal for quantifying the biomass of woodlands due to the differential interaction of microwaves with excurrent and decurrent forms. However, retrieval of component biomass may be possible by considering the specific interaction of microwaves of different frequency and polarisation with the different components. More reliable estimates of biomass are expected in relatively pure stands of species with similar structure (e.g., C. glaucophylla woodlands where trunk ground-scattering occurs and a greater proportion of the biomass is consistently allocated to the trunks).

### 14.6 Potential of future algorithms and sensors

- For mapping biomass, the use of empirical relationships is relatively limited above 60-100 Mg ha<sup>-1</sup>, as saturation of the SAR return (at lower frequencies) is typical and considerable scatter is evident. More reliable retrieval will occur at a biomass of ~ < 50 Mg ha<sup>-1</sup>. Even so, for woodlands below 100 Mg ha<sup>-1</sup>, broad biomass classes can be mapped to a level of accuracy acceptable for most greenhouse gas accounting purposes. For mapping biomass and also structural attributes, the use of SAR segmentation algorithms (e.g., Dong et al. 1998) is recommended. A combination of Landsat-derived FPC and/or C-band HV and L-band and/or P-band data allows differentiation (and mapping) of early regenerating woodlands (e.g., A. harpophylla regrowth), from woodlands with high biomass and FPC.
- For enhanced mapping of biomass, the use of SAR inversion models is a preferred option as pixel-based measures of both canopy and trunk

biomass (and related attributes such as stem density) can be obtained by using the information content of all SAR frequencies and polarisations. Direct mapping of these attributes can therefore be achieved.

As spaceborne L-band SAR sensors are not currently in operation, regional mapping of biomass is, at present, best achieved using FPC data derived from optical sensors (e.g., Landsat ETM+). However, with the launch of NASDA's ALOS PALSAR in September 2004, and continued acquisition of data by ENVISAT ASAR data, radar data layers (i.e., L-band and C-band dual polarimetry and FPC) appropriate for spatial quantification of structural attributes and biomass will become available. From these datasets, biomass can either be quantified spatially based on empirical relationships between SAR and biomass and/or FPC or through SAR inversion.

In summary, this thesis has provided considerable insight into the species/community composition, structure and biomass of woodlands at Injune and greater knowledge of their dynamics. This information has assisted the interpretation of both the SAR and optical data in the quest for better understanding the information content of these data and has led to the formulation and development of ideas and procedures for mapping key attributes of woodlands across the landscape. The development of SAR inversion models is regarded as the optimal approach to mapping, although further refinement is required.

# References

ABS (2001) Australian Bureau of Statistics (Accessed 2001). URL: <u>http://www.abs.gov.au/AUSSTATS</u>

Australian State of the Environment Committee (2001) Australia State of the Environment 2001, Independent Report to the Commonwealth Minister for the Environment and Heritage, CSIRO Publishing on behalf of the Department of the Environment and Heritage, Canberra.

ACF (2001) Australian Land clearing, A Global Perspective: Latest Facts and Figures. Australian Conservation Foundation (ACF), Melbourne. URL: <u>http://www.acfonline.org.au</u>

AFFA (2004) Appendix 1 ILZ Map and Description, Australian Government Department of Agriculture, Forestry and Fisheries URL: <u>http://www.affa.gov.au/content/print.cfm?objectid=D1557A86-3336-4040-839386168E8003C7&showdocs=all</u>

AGO (2002a) National Greenhouse Gas Inventory 2000 - Land use change and forestry: 2000 Inventory and trends. URL:

http://www.greenhouse.gov.au/inventory/2000/facts/pubs/05.pdf

AGO (2002b) Australian Greenhouse Office Climate Change, The Global Picture URL:

http://www.greenhouse.gov.au/science/impacts/overview/pubs/overview1.pdf

AGO (2002c) National Carbon Accounting System (NCAS) Methods for EstimatingLandUseChangeEmissions.URL:http://www.greenhouse.gov.au/ncas/reports/pubs/tr22final.pdf

AGO (2002d) Field Measurements and Procedures. Bush for Greenhouse: Field Measurement Procedures for Carbon Accounting, Part Two, Version 1. URL: <a href="http://www.greenhouse.gov.au/land/bush\_workbook\_a3/\_inc/pdf/part\_two.pdf">http://www.greenhouse.gov.au/land/bush\_workbook\_a3/\_inc/pdf/part\_two.pdf</a>

ARMSTON, J. D., DANAHER, T.J., GOULEVITCH, B.M., BYRNE, M.I. (2002) Geometric correction of Landsat MSS, TM, AND ETM+ imagery for mapping of woody vegetation cover and change detection in Queensland. Proceedings of the 11th Australasian Remote Sensing and Photogrammetry Conference, Brisbane, Australia.

ASNER, G. P., WESSMAN, C.A., PRIVETTE, J.L. (1997) Unmixing the directional reflectance of AVHRR sub-pixel landcover. IEEE Trans. Geoscience and Remote Sensing 35(4): 868-878.

ASSMANN, E. (1970. The Principles of forest yield study. Pergamon Press.

ATTIWELL, P. M. (1966) A method for estimating crown weight in Eucalyptus and some implications of relationships between crown weight and stem diameter. Ecology 47: 795-804.

AUSTIN, J. M., MACKEY, B.G., VAN NIEL, K.P. (2002) Estimating forest biomass using satellite radar: an exploratory study in a temperate Australian Eucalyptus forest. Forest Ecology and Management 6040: 1-9.

AVERY, T.E., BERLIN, G. L. (1992) Fundamentals of Remote Sensing and Airphoto Interpretation, 5th Edition. Macmillian Publishing Company, New York.

AVERY, T. E., BURKHART, H. E. (1994) Forest Measurements. McGraw-Hill New York.

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BAKER, J. R., MITCHELL, P.L., CORDEY, R.A., GROOM, G.B., SETTLE, J.J., STILEMAN, M.R. (1994) Relationships between physical characteristics and polarimetric radar backscatter for Corsican pine stands in Thetford Forest, U.K. International Journal of Remote Sensing 15: 2827-2849.

BALZTER, H., BAKER, J.R., HALLIKAINEN, M., TOMPPO, E. (2002) Retrieval of timber volume and snow water equivalent over a Finnish boreal forest from airborne polarimetric Synthetic Aperture Radar. International Journal of Remote Sensing 23(16): 3185–3208.

BARSON, M. M., HAIPOLA, D., RANDALL, L.A., HEFFEMAN, G. (1998) Mapping land use for the Australian continent using Landsat Mapper data. Proceedings 9th Australasian Remote Sensing and Photogrammetry Conference, 1561.

BASKERVILLE, G. L. (1972) Use of logarithmic regression in the estimation of plant biomass. Canadian Journal of Forestry Research 2: 49-53.

BEAUCHAMP, J. J., OLSEN, J.S. (1973) Corrections for bias in regression estimates after logarithmic transformation. Ecology 54: 1403-1407.

BEAUDOIN, A., LE TOAN, T., GOZE, S., NEZRY, E., LOPES, A., MOUGIN, E., HSU, C.C., HAN, H.C., KONG, J.A., SHIN, R.T. (1994) Retrieval of forest biomass from SAR data. International Journal of Remote Sensing 15: 2777-2796.

BEAUDOIN, A., CASTEL, T., DESHAYES, M., STUSSI, N., STACH, N., LE TOAN, T. (1995) Biomass retrieval over hilly terrain from spaceborne SAR data. First International Workshop on Retreival of bio and geophysical parameters from SAR data for land applications, Toulouse France.

BEERS, T., MILLER, C. (1964) Point Sampling: Research results, Theory and Applications. Research Bulletin. No. 786, Purdue University, Lafayette, IN. 56p.

References

BENALLEGUE, M., TACONET, O., VIDAL-MADJAR, D., NORMAND, M. (1995) The use of radar backscattering signals for measuring soil moisture and surface roughness. Remote Sensing of Environment 53: 61-68.

BERGEN, K. M., DOBSON, M.C., PIERCE, L.E., ULABY, F.W. (1998) Characterising carbon in a northern forest by using SIR-C/X-SAR imagery. Remote Sensing of Environment 63: 24-39.

BERGEN, K. M., DOBSON, C.M. (1999) Integration of remotely sensed radar imagery in modeling and mapping of forest biomass and net primary production. Ecological Modelling 122: 257-274.

BERNARDO, A. L., REIS, M.G.F., REIS, G.G., HARRISON, R.B., FIRME, D.J. (1998) Effect of spacing on growth and biomass distribution in Eucalyptus camaldulensis, E. pellita and E. urophylla plantations in southeastern Brazil. Forest Ecology and Management 104: 1-13.

BINDLISH, R., BARROS, A.P. (1999) Sub-pixel variability of remotely sensed soil moisture: an inter-comparison study of SAR and ESTAR. IEEE Trans. Geoscience and Remote Sensing 4:1917 -1920.

BINDLISH, R., BARROS, A.P. (2000) Multi-frequency soil moisture inversion from SAR measurements with the use of IEM. Remote Sensing of Environment 71: 67-88.

BOLAND, D. J., BROOKER, M.I.H., CHIPPENDALE, G.M., HALL, N., HYLAND, B.P.M., JOHNSTON, R.D., KLEINIG, D.A., TURNER, J.D. (1984) Forest Trees of Australia. Thomas Nelson, Melbourne.

BORNER, T., JOHNSON, M.G., RYGIEWICZ, P.T., TINGEY, D.T., JARRELL, G.D. (1996) A two-probe method for measuring water content of thin forest

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floor litter layers using time domain reflectometry. Soil Technology 9: 199-207.

BOULTER, S. L., WILSON, J., WESTRUP, J., ANDERSON, E.R., TURNER, E.J., SCANLAN, J.C. (2000) Native Vegetation Management in Queensland, Background, Science and Values. Department of Natural Resources, Brisbane.

BROWN, S. (1997) Estimating biomass and biomass change of tropical forests: a primer. United Nations Food and Agriculture Organisation (FAO) Forestry Paper 134: 55.

BUREAU OF METEOROLOGY (2000) URL: http://www.bom.gov.au (Accessed April 2000)

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS (1968) 1:250000 Geological Series-Explanatory notes. Canberra.

BURROWS, W. H., COMPTON, J.F., HOFFMAN, M.B., BACK, P.V., TAIT, L.J. (1998) Allometric relationships and community biomass estimates for some dominant eucalypts in Central Queensland woodlands. (unpublished manuscript).

BURROWS, W. H., HOFFMAN, M.B., COMPTON, J.F., BACK, P.V., TAIT, L.J. (2000) Allometric relationships and community biomass estimates for some dominant eucalypts in central Queensland woodlands. Australian Journal of Botany 48: 707-714.

BURROWS, W.H., HOFFMAN, M.B., COMPTON, J.F., BACK, P.V. (2001) Allometric relationships and community biomass stocks in White Cypress Pine (Callitris glaucophylla) and associated eucalypts of the Carnarvon area – South Central Queensland, National Carbon Accounting System, Technical Report, 33, Canberra, Australia.

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CAMPBELL, N. A. (1993) Biology. 3<sup>rd</sup> Edition, Benjamin/Cummings, Redwood City.

CASTEL, T., MARTINEZ, J., BEAUDOIN, A., WEGMULLER, U., STROZZI, T. (2000) ERS INSAR Data for Remote Sensing Hilly Forested Areas. Remote Sensing of Environment 73: 73-86.

CASTEL, T., BEAUDOIN, A., FLOURY, N., LE TOAN, T., CARAGLIO, Y., BARCZI, J. (2001) Deriving forest canopy parameters for backscatter models using the AMAP architectural plant model. IEEE Trans. Geoscience and Remote Sensing 39: 571-583.

CASTEL, T., GUERRA, F., CARAGLIO, Y., HOULLIER, F. (2002) Retrival biomass of a large Venezuelan pine plantation using JERS-1 SAR data. Analysis of forest structure impact on radar signature. Remote Sensing of Environment 79: 30-41.

CEULEMANS, R., McDONALD, A.J.S., PEREIRA, J.S. (1996) A Comparison among Eucalypt, Poplar and Willow characteristics with particular reference to a coppice growth-modelling approach. Biomass and Bioenergy 11: 215-231.

CHAMPION, I., GUYON, D., RIOM, J., LE TOAN, T., BEAUDOIN, A. (1998) Effect of forest thinning on the radar backscattering coefficient at L-band. International Journal of Remote Sensing 19: 2233-2238.

CHIBA, Y. (1998) Architectural analysis of relationship between biomass and basal area based on pipe model theory. Ecological Modelling 108: 219-225.

CORFEE-MORLOT, J., HOHNE, N. (2003) Climate Change: long term targets and short term commitments. Global Environmental Change 13: 277-293.

COLLETT, L. J., GOULEVITCH, B.M., DANAHER, T.J. (1998) SLATS radiometric correction: A semi-automated, multi-stage process for the standardisation of temporal and spatial radiometric differences. 9th Australasian Remote Sensing and Photogrammetry Conference.

COLWELL, R. N. (1983) Manual of Remote Sensing. Volume I: theory, instruments and techniques. Volume II: interpretation and applications. American Society of Photogrammetry, Falls Church, VA.

CRONIN, N. L. R., LUCAS, R.M., MILNE A.K., WITTE, C. (2000) Relationships between the component biomass of woodlands in Australia and data from airborne and spaceborne SAR. International Geoscience and Remote Sensing Symposium (IGARSS), Hawaii.

DANAHER, T., XIAOLIANG, W., CAMPBELL, N. (2001) Bi-directional reflectance distribution function approaches to radiometric calibration of Landsat ETM+ imagery. Proceedings of the 2001 IEEE International Geoscience and Remote Sensing Symposium, Sydney, Australia.

DE MESQUITA, R., WORKMAN, S.W., NEELY, C.L. (1998) Slow litter decomposition in a Cecropia-dominated secondary forest of central Amazonia. Soil Biology and Biochemistry 30(2): 167-175.

DELUCIA, E. H., MAHERALI, H., CAREY, E.V. (2000) Climate-driven changes in biomass allocation in pines. Global Change Biology 6: 587-593.

DILWORTH, J. R., BELL, J.F. (1971) Variable probability sampling - variable plot and three P, Corvalis: OSU Book Stores.

DOBSON, M. C., ULABY, F.T., LE TOAN, T., BEAUDOIN, A., KASISCHKE, E.S., CHRISTENSEN, N. (1992) Dependance of Radar backscatter on coniferous

forest biomass. IEEE Trans. Geoscience and Remote Sensing 30: 412-415.

DOBSON, M. C., ULABY, F.T., PIERCE, L.E. (1995) Land-cover Classification and Estimation of Terrain Attributes Using Synthetic Aperture Radar. Remote Sensing of Environment 51(1): 199-214.

DONG, Y., RICHARDS, J.A. (1995) Studies of the cylinder-ground double bounce scattering mechanism in forest backscatter models. IEEE Transactions on Geoscience and Remote Sensing 33: 229-231.

DONG, Y., FORSTER, B.C., MILNE, A.K., MORGAN, G.A. (1998) Speckle suppression using recursive wavelet transforms. International Journal of Remote Sensing 19(2): 317-330.

DONG, Y., FORSTER, B.C., MILNE, A.K. (1999) Segmentation of radar imagery using the Gaussian Markov random field model. International Journal of Remote Sensing 20: 1617-1639.

DONG, P. (2000) Test of a new lacunarity estimation method for image texture analysis. International Journal of Remote Sensing 21(17): 3369-3373.

DUBOIS, P. C., VAN ZYL, J., ENGMAN, T. (1995) Measuring soil moisture with imaging radars. IEEE Transactions Geoscience and Remote Sensing 33: 915-926.

DURDAN, S. L., VAN ZYL, J.J., ZEBKER, H.A. (1989) Modelling and observation of radar polarization signature of forested areas. IEEE Trans. Geoscience and Remote Sensing 27(3): 290-301.

DURDEN, S. L., KLEIN, J.D., ZEBKER, H. (1991) Polarimetric radar measurements of a forested area near Mount Shasta. IEEE Trans. Geoscience and Remote Sensing 29(3): 444-450.

EL-RAYES M., ULABY, F.T. (1987) Microwave Dielectric Spectrum of Vegetation Part I: Experimental observations, IEEEE Trans. Geoscience Remote Sensing, GE-25 (5): 541-549.

EVANS, D. L., FARR, T.G., VAN ZYL, J.J., ZEBKER, H.A. (1988) Radar polarimetry: Analysis tools and applications. IEEE Trans. Geoscience and Remote Sensing 26: 774-789.

EYRE, T. J., JERMYN, D., KELLY, A.L. (2000) Forest condition and habitat assessment in Queensland. Department of Natural Resources, Brisbane.

FEARNSIDE, P. M., GUIMARÃES, W.M. (1996) Carbon uptake by secondary forests in Brazilian Amazonia. Forest Ecology and Management 80: 35-46.

FEARNSIDE, P. M., BARBOSA, R.I. (1998) Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. Forest Ecology and Management 108:147-166.

FENSHAM, R. J. (1997) Aboriginal fire regimes in Queensland, Australia: analysis of the explorers' record. Journal of Biogeography 24(1): 11-22.

FENSHAM, R. J., McCOSKER, J.C., COX, M.J. (1998) Estimating Clearance of Acacia dominated ecosystems in central Queensland using Land-system mapping data. Australian Journal of Botany 46: 305-319.

FERRAZZOLI, P., GUERRIERO, L. (1995) Radar Sensitivity to Tree Geometry and Woody Volume: A Model Analysis. IEEE Transactions on Geoscience and Remote Sensing. **33** (2) :360-371.

FOODY, G. M., GREEN, R.M., LUCAS, R.M., CURRAN, P.J., HONZAK, M., DO AMARAL, I. (1997) Observations on the relationship between SIR-C radar

backscatter and the biomass of regenerating tropical forests. International Journal of Remote Sensing 18: 687-694.

FORSTER, B. C. (1998) Microwave Remote Sensing (subject lecture notes) School of Geomatic Engineering, UNSW Sydney.

FRANSSON, J. E. S., ISRAELSSON, H. (1999) Estimation of stem volume in boreal forests using ERS-1 C-band and JERS-1 L-band SAR data. International Journal of Remote Sensing 20: 123-137.

FRANSSON, J. E. S., WALTER, F., OLSSON, H. (1999) Identification of clear felled areas using SPOT P and Almaz-1 SAR data. International Journal of Remote Sensing 20(18): 3583-3593.

FREEMAN, A., VAN ZYL, J.J., KLEIN, J.D., ZEBKER, H.A., SHEN, Y. (1992) Calibration of stokes and scattering matrix format polarimetric SAR data. IEEE Trans. Geoscience and Remote Sensing 30: 531-539.

FROHLICH, M., QUEDNAU, H.D. (1995) Statistical analysis of the distribution pattern of natural regeneration in forests. Forest Ecology and Management 73: 45-57.

FUNG, A. K. (1994) Microwave scattering and emission models and their applications. Artech House, Inc. Norwood, MA.

GALLOWAY, R.W. (1974) Part1 Introduction, Lands of the Balonne-Maranoa Area, Part 7 Soils of the Balonne-Maranoa Area. In CSIRO Division of Landuse Research, Land Research Series No. 34. Lands of the Balonne-Maranoa Area, Queensland.

GALLOWAY, R.W., GUNN, R. H., PEDLEY, L. (1974) Landsystems Map. In

CSIRO Division of Landuse Research, Land Research Series No. 34. Lands of the Balonne-Maranoa Area, Queensland.

GIFFORD, R. M., HOWDEN, M. (2001) Vegetation thickening in an ecological perspective: significance to national greenhouse gas inventories. Environmental Science and Policy 4: 59-72.

GIVNISH, T. J. (1988) Adaption to sun and shade: A whole plant perspective. In Evans, J.R. (Editor) Ecology of photosynthesis in sun and shade.

GOETZ, A.F.H., HEIDEBRECHT, K.B., KINDEL, B. (1997) The effect of atmospheric correction on AVIRIS data to obtain consistent multiyear foliage chemisty results. IEEE Transactions on Geoscience and Remote Sensing pp. 1385-1388.

GOOD, N.M. (2001) Methods for estimating the component biomass of a single tree and a stand of trees using variable probability sampling techniques. Thesis (M.App.Sc.) School of Mathematical Sciences, Queensland University of Technology, Brisbane.

GOUDIE, A. (1986). The Human Impact on the Natural Environment, Basil Blackwell.

GRAETZ, R. D. (1995) Landcover disturbance over the Australian continent: a contemporary assessment. Dept. of Environment Sport and Territories, Canberra ACT. 86pp

GREEN, R. M. (1998a) The sensitivity of SAR backscatter to forest windthrow gaps. International Journal of Remote Sensing 19: 2419-2425.

GREEN, R. M. (1998b) Relationships between polarimetric SAR backscatter and

forest canopy and sub-canopy biophysical properties. International Journal of Remote Sensing 19(12): 2395-2412.

GREGOIRE, T. G., VALENTINE, H.G., FURNIVAL, G.N. (1986) Estimation of bole volume by importance sampling. Canadian Journal of Forest Research 16: 554-557.

GROVER, K. D., QUEGAN, S., YANASSE C. C. F. (1999) Quantitative estimation of tropical forest cover by SAR. IEEE Transactions on Geoscience and Remote Sensing, 37(1): 479 -490.

GUNN, R.H. (1974) Part 7 Soils of the Balonne-Maranoa Area. In CSIRO Division of Landuse Research, Land Research Series No. 34. Lands of the Balonne-Maranoa Area, Queensland.

HAACK, B., BECHDOL, M. (2000) Integrating multisensor data and RADAR texture measures for land cover mapping. Computers and Geosciences 26: 411-421.

HALLIKAINEN, M. T., ULABY, F.T., DOBSON, M.C., EL RAYES, M.A., WU, L. (1985) Microwave dielectric behaviour of wet soil- Part 1-2. IEEE Transactions on Geoscience and Remote Sensing 23: 25-46.

HALTRIN, V. I. (1998) Fresnel reflection coefficient of very turbid waters. Proceedings of the Fifth International Conference: Remote Sensing for Marine and Coastal Environments, Ann Arbor, MI, San Diego, CA, USA.

HARRELL, P. A., KASISCHKE, E.S., BOURGEAU-CHAVEZ, L.L., HANEY, E.M., CHRISTENSEN, N.L. (1997) Evaluation of approaches to estimating above ground biomass in southern pine forest using SIR-C data. Remote Sensing of Environment 59: 223-33.

HARRINGTON, R. A., FOWNES, J.H. (1993) Allometry and growth of planted versus coppice stands of four fast-growing tropical tree species. Forest Ecology and Management 126: 349-359.

HARRINGTON, G. (1979) Estimation of above ground biomass of trees and shrubs in Eucalyptus populnea (F. Muell). Woodland by regression of mass on trunk diameter and plant height. Australian Journal of Botany 2: 135-143.

HOEKMAN, D. H., QUINONES, M.J. (2000) Landcover type and biomass classification using AIRSAR data for evaluation of monitoring scenarios in the Columbian Amazon. IEEE Trans. Geoscience and Remote Sensing 38(2): 685-696.

HUBBARD, S. S., PETERSON, JR., MAJER, E. L., ZAWISLANSKI, P.T., WILLIAMS, K.H., ROBERTS, J., WOBBER, F. (1997) Estimation of permeable pathways and water content using tomographic radar data. The Leading Edge 16: 1623-1628.

HUSSIN, Y. A., REICH, R.M., HOFFER, R.M. (1991) Estimating slash pine biomass using radar backscatter. IEEE Trans. Geoscience and Remote Sensing 29: 427-431.

HUTCHINSON, M. F., NIX, H.A., MCMAHON, J.P. (1992) Climatic Constraints on Cropping Systems. In Pearson, P.J. (Editor) Field Crop Ecosystems. Ecosystems of the World. Elsevier, Amsterdam. 18: 37-58.

HYYPPA, J., HYYPPA, H., INKINEN, M., ENGDAHL, M., LINKO, S., ZHU, Y. (2000) Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. Forest Ecology and Management 128 (1-2): 109-120.

IMHOFF, M. L. (1995a) A theoretical analysis of the effect of forest structure on Synthetic Aperture Radar backscatter and the remote sensing of biomass. IEEE Trans. Geoscience and Remote Sensing 33(2): 341-352.

IMHOFF, M. L. (1995b) Radar backscatter and biomass saturation: Ramifications for global biomass inventory. IEEE Trans. Geoscience and Remote Sensing 33(2): 511-518.

IPCC (2001) Climate change 2001, The scientific basis: Summary for policymakers, URL: <u>http://www.grida.no/climate/ipcc\_tar/wg2/pdf/wg2TARspm.pdf</u> Part of the Working Group I contribution to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

ISRAELSSON, H., ASKNE, J., SYLANDER, R. (1994) Potential of SAR for forest bole volume estimation. International Journal of Remote Sensing 15: 2809-2826.

JACQUEMOUD, S., VERDEBOUT, J., SCHMUCK, G., REOLI, G., HOSGOOD, B., HORNIG, S.E. (1994) Investigation of leaf biochemistry by statistics. IEEE Transactions on Geoscience and Remote Sensing pp. 1239-1249.

JARVIS, P. G., LEVERENZ, J.W. (1983) Productivity of temperate, deciduous and evergreen forest. In Lange, O.L., Nobel, P.S., Osmond, C.B., Ziegler, H (Editors). Physiological Plant Ecology IV. Encyclopedia of Plant Physiology. Springer, New York. 2D: 233-280.

JOHNSON, R. W. (1964) Ecology and Control of Brigalow in Queensland. Department of Primary Industry, Brisbane.

JONES, K. L. (2000) Aerial photography interpretation for the Injune Remote Sensing

Sampling Strategy. Forest Ecosystem Research and Assessment Technical Report No. 00129, Queensland Department of Natural Resources and Mines, Indooroopilly, Brisbane.

KARAM, M. A., AMAR, F., FUNG, A.K., MOUGIN, E., LOPES, A., LE VINE, D.M., BEAUDOIN, A. (1995) A microwave polarimetric scattering model for forest canopies basd on vector radiative transfer theory. Remote Sensing of Environment 53: 16-30.

KASISCHKE, E. S., CHRISTENSEN, N.L., HANEY, E.M. (1994) Modelling of Geometric Properties of Loblolly Pine Tree and Stand Characteristics for Use in Radar Backscatter Studies. IEEE Trans. Geoscience and Remote Sensing 32(4): 800-822.

KASISCHKE, E. S., MELACK, J. M., DOBSON, M. C. (1997) The use of imaging radars for ecological applications—a review. Remote Sensing of Environment 59: 141-156.

KEELING, C. D., WHORF, T.P. (2001) Atmospheric CO<sub>2</sub> records from sites in the SIO air sampling network. In: Trends: A Compendium of Data on Global Change. Oak Ridge, Tenn., U.S.A., Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA. URL: <u>http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm</u>

KEENAN, R.J. (2002) Historical vegetation dynamics and the carbon cycle: current requirements and future challenges for quantifying carbon fluxes in Australian terrestrial ecosystems. Australian Journal Botany 50:533-544.

KELLER, M., PALACE, M., HURTT, G. (2001) Biomass estimation in the Tapajos National Forest, Brazil- Examination of sampling and allometric uncertainties. Forest Ecology and Management 154: 371-382.

KENDALL-SNELL, J. A., BROWN, J.K. (1978) Comparison of tree biomass estimators- DBH and sapwood area. Forest Science 24: 455-457.

KING, D. (1981) Tree dimensions: maximising the rate of height growth in dense stands. Oecologica 51: 351-356.

KING, D. (1991) Tree allometry, leaf size and adult tree size in old-growth forests of western Oregon. Tree Physiology 9: 369-381.

KIRSCHBAUM, M. U. F. (2000) What contribution can tree plantations make towards meeting Australia's commitments under the Kyoto Protocol. Environmental Science and Policy 3: 83-90.

KLUTE, A. (1986) Methods of soil analysis Part 1- Physical and Mineralogical methods. Soil Science Society of America, Madison.

KOHAMA, T. (1991) A functional model describing sapling growth under a tropical forest canopy. Functional Ecology 5: 83-90.

KOHEN, J. L. (1995) Aboriginal Environmental Impacts. UNSW Press, Sydney.

KRAMER, P. J., KOZLOWSKI, T. (1979) Physiology of woody plants. Academic Press, New York.

KUHNELL, C., B. GOULEVITCH, T. DANAHER, HARRIS, D. (1998) Mapping woody vegetation cover over the State of Queensland using Landsat TM. 9th Australasian Remote Sensing and Photogrammetry Conference.

KUMAR, B. M., GEORGE, S.J., JAMALUDHEEN, V., SURESH, T.K. (1998) Comparison of biomass production, tree allometry and nutrient use efficiency

References

of multipurpose trees grown in woodlot and silvopastoral experiments in Kerala, India. Forest Ecology and Management, 112: 145-163.

KUPLICH, T. M., SALVATORI, V., CURRAN, P.J. (2000) JERS-1/SAR backscatter and its relationship with biomass of regenerating forests. International Journal of Remote Sensing 21(12): 2513-2518.

KUULUVAINEN, T., PENTTINEN, A., LEINONEN, K., NYGREN, M. (1996) Statistical Opportunities for Comparing Stand Structural Heterogeneity in Managed and Primeval Forests: An Example from Boreal Spruce Forest in Southern Finland. Silva Fennica 30(2-3): 315-328.

LADEKARL, U. I. (1998) Estimation of the components of soil water balance in a Danish oak stand from measurements of soil moisture using TDR. Forest Ecology and Management 104: 227-238.

LANDSBERG, J. J., WARING, R.H. (1997) A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95: 209-28.

LANDSBERG, J. J., GOWER, S.T. (1997) Applications of physiological ecology to forest management. Academic press, San Diego.

LE TOAN, T. L., BEAUDOIN, A., RIOM, J., GUYON, D. (1992) Relating forest biomass to SAR data. IEEE Trans. Geoscience and Remote Sensing 30: 403-411.

LEECH, J. W. (1996) Generalized Importance Sampling. Forest Ecology and Management 86: 221-227.

LI, W., BENIE, G.B., HE, D., WANG, S., ZIOU, D., HUGH, Q., GWYN, J. (1999) Watershed-based hierarchical SAR image segmentation. International Journal of

Remote Sensing 20: 3377-3390.

LOZANO-GARCIA, D. F., HOFFER, R.M. (1993) Synergistic effects of combined Landsat-TM and SIR-B data forest resources assessment. International Journal of Remote Sensing 14: 2677-2694.

LUCAS, R.M., CURRAN, P.J., HONZAK, M., FOODY, G.M., DO AMARAL, I., AMARAL, S. (1996) Disturbance and recovery of tropical forests: Balancing the carbon account. In J.H.C. Gash, C.A. Nobre, J.M. Roberts and R.L. Victoria (Editors) Amazonian Deforestation and Climate, John Wiley and Sons, Chichester, 383-398.

LUCAS, R. M., CRONIN, N., MILNE, A.K., DONG, Y., WITTE, C. (1999) Estimating woodland biomass stocks in Queensland using Synthetic Aperture Radar (SAR) Data. Report to the Australian Bureau of Resource Sciences, Canberra, 54 pp.

LUCAS, R. M., MILNE, A.K., CRONIN, N., WITTE, C., DENHAM, R. (2000a) The Potential of Synthetic Aperature Radar (SAR) Data for Quantifying the Above Ground Biomass of Australia's Woodlands. The Rangeland Journal 22: 124-140.

LUCAS, R. M., CRONIN, N., MILNE, A.K., DONG, Y., WITTE, C., DENHAM, R. (2000b) Carbon losses from landuse change in Australia : A role for SAR. International Geoscience and Remote Sensing Symposium (IGARSS), Hawaii.

LUCAS, R.M., TICKLE, P., LEE, A., AUSTIN, J., WITTE, C., JONES, K., CRONIN, N., MOGHADDAM, M., MILNE, A.K. (2002) Use of AIRSAR (POLSAR) data for quantifying the biomass of woodlands, Queensland, Australia. The AIRSAR Workshop, Jet Propulsion Laboratory (JPL), Pasadena, California USA April, 2002.

LUCAS, R.M., LEE, A., MILNE, A.K., CRONIN, N., MOGHADDAM, M. (2003) Remote sensing to support Australia's commitment to international agreements: A role for Synthetic Aperture Radar. Proceedings, International Geoscience and Remote Sensing Symposium (IGARSS), Toulouse (CDROM).

LUCKMAN, A. J., FRERY, A.C., YANASSE, C.C.F., GROOM, G.B. (1997a) Texture in airborne SAR imagery of tropical forest and its relationship to forest regeneration stage. International Journal of Remote Sensing 18: 1333-1349.

LUCKMAN, A., BAKER, J., KUPLICK, T.M., YANESSE, C., FRERY, A.C. (1997b) A study of the relationship between radar backscatter and regenerating tropical forest biomass for spaceborne SAR instruments. Remote Sensing of Environment, 60: 1-13.

MAKINEN, H. (1997) Possibilities of competition indices to describe competitive differences between Scots pine families. Silva Fennica 31(1): 43-52.

MARGOLIS, H. A., GAGNON, R.R., POTHIER, D., PINEAU, M. (1988) The adjustment of growth, sapwood area, heartwood area and saturated permeability of balsam fir after different intensities of pruning. Canadian Journal of Forest Research 18: 723-727.

MARTINEZ, J., FLOURY, N., LE TOAN, T., BEAUDOIN, A., HALLIKAINEN, M.T. (2000) Measurements and modelling of vertical backscatter distribution in forest canopy. IEEE Trans. Geoscience and Remote Sensing 38: 710-719.

McDONALD, K.S., ULABY, F.T. (1993) Radiative transfer modelling of discontinuous tree canopies at microwave frequencies. International Journal of Remote Sensing 14 (11): 2097-2128.

McMAHON, T. A., KRONAUER, R.E. (1976) Tree Structure: deducing the principle of mechanical design. Journal of Theoretical Biology 59: 443-466.

MEADE, N. G., HINZMAN, L.D, KANE, D.L. (1999) Spatial estimation of soil moisture using SAR in Alaska. Adv. Space Res. 24(7): 935-940.

MEDHURST, J. L., BATTAGLIA, M., CHERRY, M.L., HUNT, M.A., WHITE, D.A., BEADLE, C.L. (1999) Allometric relationships for Eucalyptus nitens (Deane and Maiden) Maiden plantations. Trees 14: 91-101.

MICHELSON, D. B., LILJEBERG, B.M., PILESJO, P. (2000) Comparison of algorithms for classifying swedish landcover using Landsat TM and ERS-1 SAR data. Remote Sensing of Environment 71: 1-15.

MICROCAL SOFTWARE INC. (1997) Data Analysis and Technical Graphics, User's Manual, Version 5. Northampton, MA, US. 694pp.

MOGHADDAM, M., DURDEN, S., ZEBKER, H. (1994) Radar measurement of forested areas during OTTER. Remote Sensing of Environment 47: 154-166.

MOGHADDAM, M., SAATCHI, S. (1995) Analysis of Scattering Mechanisms in SAR Imagery over Boreal Forest: Results from BOREAS '93. IEEE Transactions on Geoscience and Remote Sensing 5: 1290-1295.

MOGHADDAM, M., SAATCHI, S. (1999) Monitoring Tree Moisture Using an Estimation Algorithm Applied to SAR Data from BOREAS. IEEE Transactions on Geoscience and Remote Sensing 37(2): 901-916.

MOGHADDAM, M., DUNGAN, J., COUGHLAN, J. (1999) Fusion of AIRSAR and TM data for parameter classification and estimation in dense and hilly forests. IEEE Trans. Geoscience and Remote Sensing: 305-307. MOGHADDAM, M., LUCAS, R.M. (2003) Quantifying the biomass of Australian subtropical woodlands using SAR inversion models. Proceedings International Geoscience and Remote Sensing Symposium (IGARSS), Toulouse, France (CDROM).

MORAN, S.M., HYMER, D.C., QI, J., KERR, Y. (2002) Comparison of ERS-2 SAR and Landsat TM imagery for monitoring agricultural crop and soil conditions. Remote Sensing of Environment, 79:243-252.

MORATAYA, R., GALLOWAY, G., BERNINGER, F., KANNINEN, M. (1999) Foliage biomass- sapwood (area and volume) relationships of Tectona grandis L.F. and Gmelina arborea Roxb. : silvicultural implications. Forest Ecology and Management 113: 231-239.

NCAS (2000) Technical Report No. 17: Synthesis of Allometrics, Review of Root Biomass and Design of Future Woody Biomass Sampling Strategies. Canberra, Australian Greenhouse Office. URL:<u>http://www.greenhouse.gov.au/challenge/tools/workbook/factorsmethod</u> \_section2-2.html

NCAS (2002) GREENHOUSE GAS EMISSIONS FROM LAND USE CHANGE IN AUSTRALIA: Results of the National Carbon Accounting System. Canberra, Australian Greenhouse Office. URL: <u>http://www.greenhouse.gov.au/ncas/</u>

NELDNER, V. J. (1984) Vegetation survey of Queensland: South Central Queensland. Queensland Botany Bulletin. Queensland Department of Primary Industries, Brisbane.

NEUMANN, M., STARLINGER, F. (2001) The significance of different indices for stand structure and diversity in forests. Forest Ecology and Management 145: 91-106.

NEZRY, E., MOUGIN, E., LOPES, A., GASTELLU-ETCHEGORRY, J.P. (1993) Tropical vegetation mapping with combined visible and SAR spaceborne data. International Journal of Remote Sensing 14: 2165-2184.

NFI (2003) National Forest Inventory -Forests at a glance. Canberra. URL: <a href="http://www.affa.gov.au/corporate\_docs/publications/pdf/rural\_science/nfi/ata\_glance.pdf">http://www.affa.gov.au/corporate\_docs/publications/pdf/rural\_science/nfi/ata\_glance.pdf</a>

NGGI (1997) Carbon Dioxide from the Biosphere; In National Greenhouse Gas Inventory, Workbook 4.2. Environment Australia, Canberra.

NIIENMENTS, U. (1998) Growth of young trees of Acer platanoides and Quercus robur along a gap-understorey continuum: interrelationships between allometry, biomass partitioning, nitrogen and shade tolerance. International Journal of Plant Sciences 158: 318-338.

NIKLAS, K. J. (1995) Size-dependant Allometry of tree height, diameter and trunk taper. Annals of Botany 75: 217-227.

Nix, H. (1994) The Brigalow. In Dovers, S. (Editor) Australian Environmental History: Essays and Cases. Oxford University Press, Melbourne. pp. 198-235.

NLWRA (2001a) Australian Native Vegetation Assessment 2001, National Land and Water Resources Audit, published for the Commonwealth of Australia. URL:

http://audit.ea.gov.au/anra/vegetation/docs/native\_vegetation/Nat\_Veg\_Contents.cfm

NLWRA (2001b) Australian dryland salinity assessment 2000, National Land and Water Resources Audit, published for the Commonwealth of Australia. URL: <a href="http://audit.ea.gov.au/ANRA/land/docs/national/Salinity\_Contents.html">http://audit.ea.gov.au/ANRA/land/docs/national/Salinity\_Contents.html</a>

OH, Y., SARABANDI, K., ULABY, F.T. (1992) An empirical model and inversion tecnique for radar scattering from bare soil surfaces. IEEE Transactions Geoscience and Remote Sensing 30: 370-382.

OKER-BLOM, P., KELLOMÄKI, S. (1982) Theoretical computations on the role of crown shape in the absorption of light by forest trees. Math. Biosci 59: 291-311.

PALOSCIA, S., MACELLONI, G., PAMPALONI, P., SIGISMONDI, S. (1999) The potential of C- and L-band SAR in estimating vegetation biomass: The ERS-1 and JERS-1 experiments. IEEE Trans. Geoscience and Remote Sensing 37(4): 2107-2110.

PAUDYAL, D., KUHNELL, C., DANAHER, T. (1997) Detecting change in woody vegetation in Queensland using Landsat TM imagery. Proceeding of the North Australasian Remote Sensing and GIS conference (NARGIS), Cairns Queensland.

PEDLEY, L. (1974) Part 9 Pasture Lands of the Balonne-Maranoa Area. In CSIRO Division of Landuse Research, Land Research Series No. 34. Lands of the Balonne-Maranoa Area, Queensland.

PERTTUNEN, J., SIEVANEN, R., NIKINMAA, E. (1998) LIGNUM :a model combining the structure and functioning of trees. Ecological Modelling 108: 189-198.

POPE, K. O., REY-BENAYAS, J.M., PARIS, J.F. (1994) Radar remote sensing of forest and wetland ecosystems in the Central American Tropics. Remote Sensing

of Environment 48: 205-219.

PROISY, C., MOUGIN, E., FROMARD, F., KARAM, M.A. (2000) Interpretation of polarimetric radar signatures of mangrove forests. Remote Sensing of Environment 71: 56-66.

PULLIAINEN, J. T., MIKKELA, P.J., HALLIKAINEN, M.T., IKONEN, J. (1996) Seasonal Dynamics of C-band Backscatter of Boreal Forests with Applications to Biomass and Soil Moisture Estimation. IEEE Transactions on Geoscience and Remote Sensing 34: 758-769.

PULTZ, T. J., CREVIER, Y., BROWN, R.J., BOISVERT, J. (1997) Monitoring local environmental conditions with SIR-C/X-SAR. Remote Sensing of Environment 59: 248-255.

QLD DNRM (1999a) The Statewide Landcover and Trees Study (SLATS), Queensland Department of Natural Resources and Mines. URL: <u>http://www.nrm.qld.gov.au/slats/pdf/paste9597-11.pdf</u>

QLD DNRM (1999b) NRM Facts, Queensland Department of Natural Resources and Mines. URL: <u>http://www.nrm.qld.gov.au/factsheets/index.php</u>

QLD DNRM (2000) Digital coverages and imagery, supplied by Queensland Department of Natural Resources and Mines.

QLD DNRM (2003) The Statewide Landcover and Trees Study (SLATS), Queensland Department of Natural Resources and Mines URL: http://www.nrm.qld.gov.au/slats/pdf/slats9901.pdf

QLD DPI (1984) Queensland Department of Primary Industry (1984) The Brigalow belt of Australia, Royal Society of Queensland, Brisbane. RANSON, K. J., SUN, G. (1994a) Mapping Biomass of a Northern Forest Using Multifrequency SAR data. IEEE Trans. Geoscience and Remote Sensing 32(2): 388-396.

RANSON, K. J., SUN, G. (1994b) Northern forest classification using temporal multifrequency and multipolarimetric SAR images. Remote Sensing of Environment 47: 142-153.

RANSON, K. J., SUN, G., WEISHAMPEL, J.F., KNOX, R.G. (1997) Forest biomass from combined ecosystem and radar backscatter modelling. Remote Sensing of Environment, 59: 118-133.

RANSON, K. J., SUN, G (1997) An Evaluation of AIRSAR and SIR-C/X-SAR Images for MApping Northern Forest Attributes in Maine, USA. Remote Sensing of Environment 59: 203-222.

RANSON, K. J., SUN, G., KHARUK, V.I., KOVACS, K. (2001) Characterisation of forests in Western Sayani Mountains, Siberia from SIR-C SAR data. Remote Sensing of Environment 75: 188-200.

RAUSTE, Y., HAME, T., PULLIAINEN, J., HEISKA, K., HALLIKAINEN, M. (1994) Radar based forest biomass estimation. International Journal of Remote Sensing 15: 2797-2808.

REPPERT, M.P., MORGAN, D.F., TOKSOZ, N.M. (2000) Dielectric constant determination using ground-penetrating radar reflection coefficients. Journal of Applied Geophysics 43: 189-197.

RICHARDS, J.A., SUN, G.Q., SIMONETT, D.S. (1987) L-band radar backscatter

modeling of forest stands. IEEE Trans. Geoscience and Remote Sensing 25: 487-498.

RICHARDS, J. A. (1990) Radar Backscatter modelling of forests: a review of current trends. International Journal of Remote Sensing 11: 1299-1312.

RIGNOT, E. J. M. (2000) Effect of faraday rotation on L-band interferometric and polarimetric synthetic aperture radar data. IEEE Trans. Geoscience and Remote Sensing 38(1): 383-390.

RIGNOT, E. J., ZIMMERMANN, R., VAN ZYL, J.J. (1995) Spaceborne applications of P-band imaging radars for measuring forest biomass. IEEE Transactions on Geoscience and Remote Sensing 33: 1162-1169.

RIGNOT, E., WAY, J., WILLIAMS, C., VIERECK, L. (1994) Radar estimates of above ground biomass of boreal forests of interior Alaska. IEEE Trans. Geoscience and Remote Sensing 32: 117-1124.

ROBERTS, G. (2003) Queensland bulldozers to the Third World. The Sydney Morning Herald. Sydney.

ROSENQVIST, A., BIRKETT, C.M., BARTHOLOME, E., DE GRANDI, G. (1999) Using satellite altimetry and historical gauge data for validation of the hydrological significance of the JERS-1 SAR (GRFM) mosaics in central Africa. International Geoscience and Remote Sensing Symposium, 1999. IGARSS '99 Proceedings. 5(28):2754 – 2758.

ROSENQVIST, A., MILNE T., LUCAS R., IMHOFF, M., DOBSON C. (2003) A review of remote sensing technology in support of the Kyoto Protocol. Environmental Science & Policy, 6 (5): 441-455.

SAATCHI, S. S., SOARES, J.V., SALAS ALVES, D. (1997) Mapping Deforestation and Land-Use in Amazon Rainforest by Using SIR-C Imagery. Remote Sensing of Environment 59: 191-202.

SAATCHI, S. S., RIGNOT, E. (1997) Land cover classification of BOREAS modelling grid using AIRSAR images. Remote Sensing of Environment 35(6): 270-281.

SAATCHI, S. S., MOGHADDAM, M. (2000) Estimation of crown and stem water content and biomass of boreal forest using polarimetric SAR imagery. IEEE Trans. Geoscience and Remote Sensing 38(2): 697-709.

SADER, S. A. (1987) Forest biomass, canopy structure, and species composition relationships with multipolarisation L-band SAR data. Photogrammatic Engineering and Remote Sensing 53: 193-202.

SALAS, W.A., DUCEY, M.J., RIGNOT, E., SKOLE, D. (2002) Assessment of JERS-1 SAR for monitoring secondary vegetation in Amazonia: 1. Spatial and temporal variability in backscatter across a chrono-sequence of secondary vegetation stands in Rhondonia. International Journal of Remote Sensing 23: 1357-1379.

SAN JOSE, J. J., MONTES, R.A., FARINAS, M.R. (1998) Carbon stocks and fluxes in a temporary scaling from a savanna to a semi-deciduous forest. Forest Ecology and Management 105: 251-262.

SAN MIGUEL-AYANZ, J. (1996) Synergy of optical and polarimetric microwave data for forest resource assessment. International Journal of Remote Sensing 17: 3047-3663.

SANTOS, J.R., FREITAS, C.C., ARAUJO, L.S., DUTRA, L.V., MURA, J.C.,

GAMA, F.F., SOLER, L.S., SANT'ANNA, J.S. (2003) Airborne P-band SAR applied to above ground biomass studies in the Brazilian tropical forest. Remote Sensing of Environment 87: 482-493.

SCANLAN, J.C. (1991) Woody overstorey and herbaceous understorey biomass in Acacia harpophylla (brigalow) woodlands. Australian Journal of Ecology 16:521-529.

SCHACHT, W. H., LONG, J.N., GOBENA, A. (1992) Aboveground biomass accumulation in coppicing woodland, northeast Brazil. Forest Ecology and Management 55: 201-208.

SCHMULLIUS, C., FURRER, R. (1992) Some critical remarks on the use of Cband radar data for soil moisture detection. International Journal of Remote Sensing 13: 3387-3390.

SCHOLES, R. J. VAN DER MERWE, M.R. (1996) Sequestration of carbon in savannas and woodlands. The Environmental Professional 18: 96-103.

SCHULER, D. L., LEE, J. S., AINSWORTH, T.L. (1999) Compensation of Terrain Azimuthal Slope Effects in Geophysical Parameter Studies Using Polarimetric SAR Data. Remote Sensing of Environment. 69: 139-155.

SHINOZAKI, K., YODA, K., HOZUMI, K., KIRA, T. (1964a) A Quantitative Analysis of Plant Form- The Pipe Model Theory 1. Basic Analyses. Japanese Journal of Ecology 14(3): 97-105.

SHINOZAKI, K., YODA, K., HOZUMI, K., KIRA, T. (1964b) A Quantitative Anlalysis of Plant Form- The Pipe Model Theory 2. Further Evidence of the Theory and its Application in Forest Ecology. Japanese Journal of Ecology 14(4): 133-139.

SIEBER, A. J. (1995) From microscale to macroscale. Remote Sensing Reviews 12(1-2): 131-146.

SIMS, R. E. H., SENELWA, K., MAIAVA, T., BULLOCK, B.T. (1999) Eucalyptus species for biomass energy in New Zealand-Part 2: Coppice performance. Biomass and Bioenergy 17: 333-343.

SOARES, J. V., RENNO, C.D., FORMAGGIO, A.R., YANASSE, C.F., FRERY, A.C. (1997) An investigation of the selection of texture features for crop discrimination using SAR imagery. Remote Sensing of Environment 59: 234-247.

SONG, B., CHEN, J., DESANKER, P.V., REED, D.D., BRADSHAW, G.A., FRANKLIN, J.F. (1997) Modelling canopy structure and heterogeneity across scales: From crowns to canopy. Forest Ecology and Management 96: 217-229.

SPECHT, R. L. (1970) Vegetation. In Leeper. G.W. (Editor) The Australian Environment. CSIRO and Melbourne University Press, Melbourne. pp 44–67.

SRIVASTAVA, S. K., YOGRAJAN, N., JAYARAMAN, V., NAGESWARA RAO, P.P., CHANDRASEKHAR, M.G. (1998) On the relationship between ERS-1 SAR backscatter and surface/subsurface soil moisture variations in vertisols. Acta Astronautica 40(10): 693-699.

STANKIEWICZ, K. (2002) The use of microwave SAR images for forest decline monitoring in mountainous areas. Adv. Space Res. 29(1): 67-72.

STEINBECK, K. (1981) Short rotation forestry as a biomass source: an overview. Proceedings of 1<sup>st</sup> European Biomass Conference, Applied Science Publishers.

STRAHLER, A.H., STRAHLER, A.N. (1987) Modern Physical Geography. John Wiley and Sons, New York.

SU, Z., TROCH, P.A., DE TROCH, F.P. (1997) A method for retrieving soil moisture using active microwave data. Phys. Chem. Earth, 22(3-4): 235-239.

SUN, G., SIMONETT, D.S. (1988) A composite L-band radar backscattering model for coniferous forest stands. Photogrammatic Engineering and Remote Sensing 54: 1195-1201.

SUN, G., SIMONETT, D.S., STRAHLER, A.H. (1991) A radar backscatter model for discontinuous coniferous forests. IEEE Trans. Geoscience and Remote Sensing GE-29 (4): 639-650.

SUN, G., RANSON, K.J. (1998) Radar modelling of forest spatial patterns. International Journal of Remote Sensing 19: 1769-1791.

SUN, G., RANSON K.J., KHARUK, V.I. (2002) Radiometric slope correction for forest biomass estimation from SAR data in the Western Sayani Mountains, Siberia. Remote Sensing of Environment 79: 279-287.

SVS (2000) STAND VISUALISATION SOFTWARE (Accessed September 2000). URL: http://forsys.cfr.washington.edu/svs.html

TACONET, O., VIDAL-MADJAR, D., EMBLANCH, C., NORMAND, M. (1996) Taking into account vegetation effects to estimate soil moisture from C-band radar measurements. Remote Sensing of Environment 56: 52-56.

TAIT, L. (1999) Coppice growth of Eucalypts in semi-arid Queensland, Personal Communication (N. Cronin). DPI Rockhampton.

TAKEUCHI, S., SUGA, Y., OGURO, Y., KONISHI, T. (2000) Monitoring of New Plantation Development in Tropical Rain Forests Using JERS-1 SAR Data.

Advances in Space Research 26 (7): 1151-1154.

TER-MIKAELIAN, M. T., KORZUKHIN, M.D. (1997) Biomass equations for sixty-five North American tree species. Forest Ecology and Management 19: 1-24.

TICKLE, P. K., LEE, A., AUSTIN, J., WITTE, C., LUCAS, R.M. (2003) Using Small Footprint LiDAR and Large Scale Photography for Estimating the Biomass and Structural Attributes of Australian Forests and woodlands. Canadian Journal of Forest Research In Press.

TOPP, G.C., DAVIS, J.L., ANNAN, A.P. (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research. 16(3):547-582.

TOUZI, R., LE TOAN, T., LOPES, A., MOUGIN, E. (1992) Polarimetric discriminators for SAR images. IEEE Trans. Geoscience and Remote Sensing 30(5): 973-980.

TSAIR, F. C., CHIN, M.L. (1988) The growth and stand biomass of Casuarina plantation at Miao-Li coastal sand dune. Taiwan Forest Research Institute, Taiwan. 3: 333-343.

ULABY, F. T., ALLEN, C.T., EGER, G., KANEMASU, E. (1984) Relating the microwave backscattering coefficient to leaf area index. Remote Sensing of Environment 14: 113-133.

ULABY, F. T., MOORE, R.K., FUNG, A.K. (1986) Microwave Remote Sensing-Active and Passive. Artech House Inc, Dedham, MA. ULABY, F.T., SARABANDI, K., MCDONALD, K., WHITT, M., DOBSON, C. (1990) Michigan microwave canopy scattering model. International Journal of Remote Sensing 11: 1223-1253.

ULABY, F. T., DUBOIS, P.C., VAN ZYL, J. (1996) Radar mapping of surface soil moisture. Journal of Hydrology 184: 57-84.

UNFAO (2001) United Nations Food and Agriculture Organisation 2001, Forest Resources Assessment 2000, UNFAO, Rome; Australian Conservation Foundation 2001, Australian Land Clearing, A Global Perspective: Latest Facts and Figures, ACF, Melbourne.

UNFCC (2003) Kyoto Protocol: Status of Ratification. <u>URL:http://unfccc.int/resource/kpstats.pdf</u>

VAN DER SANDEN, J. J., HOEKMAN, D.H. (1999) Potential of Airborne radar to support the assessment of landcover in a tropical rainforest environment. Remote Sensing of Environment 68: 26-40.

VAN ZYL, J. J., ZEBKER, H.A., ELACHI, C. (1987) Imaging Radar Polarisation signatures: Theory and Observation. Radio Science 22: 529-543.

VERMOTE, E. F., TANRE, J., DEUZE, J.L., HERMAN, M., MORCRETTE, J. (1997) Second Simulation of the Satellite Signal in the Solar Spectrum, 6s: An Overview. IEEE Transactions Geoscience and Remote Sensing 35(3): 675-686.

VUCETICH, J. A., REED, D.D., BREYMEYER, A., DEGORSKI, M., MROZ, G.D., SOLON, J., ROO-ZIELINSKA, E., NOBLE, R. (2000) Carbon pools and ecosystem properties along a latitudinal gradient in northen Scots Pine (Pinus sylvestris) forests. Forest Ecology and Management 136: 135-145. WAGNER, W., LEMOINE, G., ROTT, H. (1999) A method for estimating soil moisture from ERS scatterometer and soil data. Remote Sensing of Environment 70: 191-207.

WANG, Y., DAVIS, F.W., MELACK, J.M. (1993a) Simulated and Observed backscatter at P-, L-, and C-bands from Ponderosa Pine Stands. IEEE Transactions Geoscience and Remote Sensing 31(4): 871-879.

WANG, Y., DAY, J.L., DAVIS, F.W., MELACK, J.M. (1993b) Modelling L-band radar backscatter of Alaskan boreal forest. IEEE Transactions Geoscience and Remote Sensing 31(6): 1146-1154.

WANG, Y., KASISCHKE, E.S., MELACK, J.M., DAVIS, F.W., CHRISTENSEN, N.L. (1994) The effects of changes in Loblolly Pine biomass and soil moisture on ERS-1 SAR backscatter. Remote Sensing of Environment 49: 25-31.

WANG, Y., DAVIS, F.W., MELACK, J.M, KASISCHKE, E.S., CHRISTENSEN, N.L. (1995) The effects of changes in forest biomass on radar backscatter from tree canopies. International Journal of Remote Sensing 16: 503-513.

WANG, Y., DAY, J.L., DAVIS, F.W. (1998) Sensitivity of Modeled C- and L-Band Radar Backscatter to Ground Surface Parameters in Loblolly Pine Forest. Remote Sensing of Environment 66(3): 331-342.

WARING, R. H., SCHROEDER, P.E., OREN, R. (1982) Application of the Pipe model theory to predict canopy leaf area. Canadian Journal of Forest Research 12: 556-560.

WAY, J., PARIS, J., KASISCHKE, E., SLAUGHTER, C., VIERECK, L., CHRISTENSEN, N., DOBSON, M.C., ULABY, F., RICHARDS, J, MILNE, A.K., SIEBER, A., AHERN, F.J., SIMONETT, D., HOFFER, R., IMHOFF, M., WEBER, J. (1990) The effect of changing environmental conditions on microwave signatures of forest ecosystems: preliminary results of the March 1988 Alaskan aircraft SAR experiment. International Journal of Remote Sensing 11: 1119-1144.

WHITEHEAD, D. W., EDWARDS, W.R.N., JARVIS, P.G. (1984) Conducting sapwood area, and permeability in mature Picea sitchensis and Pinus contorta. Canadian Journal of Forest Research 14: 940-947.

WITTE, C., DENHAM, R., NORMAN, P., LUCAS, R. (1998) The potential of radar imagery for mapping biomass stocks and estimating structural attributes of forests and woodlands in Queensland. Forest Ecosystem Research and Assessment, Resource Sciences Centre, Indooroopilly, Queensland. 26pp.

WU, S. T., SADER, S.A. (1987) Multipolarisation SAR data for surface feature delineation and forest vegetation characterisation. IEEE Trans. Geoscience and Remote Sensing 25: 67-76.

YOUNG, A., R.M. (1996) Environmental Change in Australia since 1788. Oxford University Press, Melbourne.

YUEH, H. A., SWARTZ, A.A., KONG, J.A., SHIN, R.T., NOVAK, L.M. (1988) Bayes classification of terrain cover using normalised polarimetric data. Journal of Geophysical Research 93: 15261-15267.

ZEBKER, H. A. VAN ZYL, J.J., HELD, D.N. (1987) Imaging radar polarimetry from wave synthesis. Journal of Geophysical Research 92(B1): 683-701.

ZEBKER, H. A. VAN ZYL, J.J. (1991) Imaging radar polarimetry: A review. IEEE Transactions Geoscience and Remote Sensing 79(11): 1583-1606. ZINK, M., KIETZMANN, H., BÖRNER, T., BLÖTSCHER, H., SEIFERT, F. (1997) Microwave Remote Sensing for Monitoring Forest Vitality. 3rd ERS Symposium, Florence.

## Appendix A

### Table A1Projection details for Injune metadata from QLDDNRM (2000)

Datum	WGS 84
Spheroid	GRS 1980
Georeferenced to:	Transverse Mercator
Scale factor at central meridian	0.9996
Longitude of central meridian	147 degrees
False Easting	500000 metres
False Northing	10000000 metres
UTM Zone	55

### Table A2Acronyms used to represent species present at the Injune study site

Species	Scientific Name	Shortened Name	Common Name
Code			
AEF		A. leiocalyx	Curracabah
	Acacia leiocalyx		
AEX		A. excelsa	Ironwood wattle
	Acacia excelsa		
AIX		A. ixiophylla	
	Acacia ixiophylla		
ANE		A. nerifolia	
	Acacia nerifolia		
BGL		A. harpophylla	Brigalow
	Acacia harpophylla		_
BLH		C. cristata	Belah
	Casuarina cristata		
BOK	Allocasuarina spp.	Allocasuarina spp.	Bull-oak
BRH		L. angustifolius	Brown hazelwood
	Lysicarpus angustifolius		
BRI		E. fibrosa (spp.	Broad-leaved red
	Eucalyptus fibrosa (spp.	fibrosa)	ironbark
	fibrosa)		
BLI	Eucalyptus fibrosa (spp.	E. fibrosa (spp.	Blue-leaved ironbark
	nubila)	nubila)	
CP-	Callitris glaucophylla	C. glaucophylla	White cypress pine
ECH	Eucalyptus chloroclada	E. chloroclada	
EDO	Eucalyptus dolichocarpa	E. dolichocarpa	
EUC	Syzygium cormiflorum	S. cormiflorum	Bumpy Satin ash

-	'ramiflorus form'		
EUS	Eucolumtus anasias	Eucalyptus spp.	
	Eucaryptus species		
FMP	Callitris glauconhylla vC		
	preissii ssp. verrucosa		
FRC	Freiber oof treitwood	F tereticornis	Forest red gum
1 KG	Eucalyptus tereticornis	L. Creteorins	i oreșt reu guin
GBO		E. microcarpa	Grev box
abo	Eucalyptus microcarpa	p	diey bon
GLI			
GTI		E. decorticans	Gum-topped ironbark
	Eucalyptus decorticans		
HAK		H. fraseri	Hakea
	Hakea fraseri		
KJG	Brachychiton populneuss	B. populneuss	Kurrajong
	spp. populneus		
NRI		E. crebra	Narrow-leaved red
	Eucalyptus crebra		ironbark
NSN	Santalana lan salatana	S. lanceolatum	
	Santaium lanceolatum		
РВХ	Fucelyntus populnes	E nonulnoo	Poplarbox
חחח		E. populliea	Detalle Deser
РРК	Opuntia tomentosa	O. tomentosa	Prickly Pear
QPM			Queensland
·	Eucalyptus exserta	E. exserta	peppermint
RBA			Rough-barked apple
	Angophora floribunda	A. floribunda	
SBA			Smooth-barked apple
	Angophora leiocarpa	A. leiocarpa	
SBX			
	Lophostemon suaveolens	L. suaveolens	
SLI			Silver-leaved ironbark
~~~~~	Eucalyptus melanophiola	E. melanophiola	
SWB	Framanhila mitchalli	E mitchalli	Sandalwood box
TDC		E. IIIItchem	
IDG	Fucalyntus dealbata	F dealhata	i umbledown gum
WAT	A coorie gpp	A cooie ann	Wattle
WAI WII	maria spp.	Alacia spp.	Wilga
VVIL	Geijera parviflora	G. parviflora	vv liga
1002	Xvlomelum	X.	Woody Pear
100%	cunninghamianum	cunninghamianum	
1010	Acacia leptostachya	A. leptostachya	
1015	Casuarina sp.		
1016	Canthium sp.		

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1018	Notelea microcarna	N microcarna	
	Tyotelea merocarpa	iv. microcarpa	

Analysis was based on the first and second codes (e.g., PBXSWB, where PBX is the first code and SWB is the second code and it represents the Eucalyptus populnea-Eremophila mitchelli association).



Figure A1 Legend for species associations in Chapter 10 and Figures in Appendix C





#### Appendix B



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# Appendix C








































## Appendix D



Figure D.1 Simplified woodland stand (Secondary Sampling Unit 81\_11) of Callitris glaucaphylla and Angophora leiocarpa.

Table D.1The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 81\_11).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-8.38	-9.47	0.00	0.00	-18.71
C VV	-6.14	-7.25	0.00	0.00	-16.46
C HV	-15.53	-15.53	0.00	0.00	
L HH	-11.13	-18.09	-23.61	-13.03	-24.65
L VV	-14.40	-16.90	-37.00	-26.65	-22.00
L HV	-26.14	-26.34	-42.58	-42.66	
P HH	-8.06	-23.88	-17.13	-8.84	-31.49
P VV	-16.08	-23.46	-34.75	-18.56	-27.76
P HV	-29.83	-31.02	-37.45	-41.67	



Figure D.2 Simplified woodland stand (Secondary Sampling Unit 114\_4) Callitris glaucaphylla and Angophora leiocarpa.

Table D.2The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 114\_4).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-9.95	-13.51	-51.05	-46.30	-18.56
C VV	-8.44	-10.98	-62.03	-59.50	-15.58
C HV	-18.53	-18.53	-63.20	-91.97	
L HH	-9.96	-19.89	-20.13	-11.44	-27.07
L VV	-13.55	-17.35	-30.77	-27.17	-23.21
L HV	-24.49	-25.11	-39.88	-34.27	
P HH	-12.22	-27.46	-25.31	-12.73	-33.72
P VV	-11.28	-27.12	-33.22	-11.83	-29.86
P HV	-29.41	-40.24	-43.39	-29.97	



Figure D.3 Simplified woodland stand (Secondary Sampling Unit 114\_12) of Callitris glaucaphylla and Angophora leiocarpa.

Table D.3	The contribution of each scattering mechanism (dB) to the overall
SAR backscat	ter at different frequencies and polarisations (Secondary Sampling
	Unit 114_12).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-7.99	-9.05	-30.48	-21.11	-19.14
C VV	-6.19	-7.42	-39.16	-31.81	-18.69
C HV	-15.83	-15.84	-44.83	-64.94	
L HH	-12.01	-18.06	-31.17	-13.91	-28.51
L VV	-15.20	-17.93	-51.82	-27.66	-25.38
L HV	-31.81	-32.52	-48.64	-40.66	
P HH	-11.60	-17.81	-24.37	-13.24	-35.45
P VV	-13.77	-17.75	-46.61	-16.79	-31.42
P HV	-29.80	-30.90	-43.96	-37.10	



Figure D.4 Simplified woodland stand (Secondary Sampling Unit 111\_12) of Callitris glaucaphylla and Eucalyptus melanophloia.

Table D.4The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 111\_12).

Freq.	Total	Branch/	Branch	Trunk	Ground
Pol.		Foliage	Ground	Ground	
C HH	-7.01	-11.86	-75.36	-64.61	-23.14
C VV	-5.67	-6.68	-88.00	-78.32	-21.13
C HV	-13.28	-13.28	-89.35	-91.20	
L HH	-7.22	-22.75	-23.86	-8.31	-25.80
L VV	-13.38	-17.34	-38.78	-17.64	-23.35
L HV	-24.40	-24.99	-38.90	-34.76	
P HH	-3.61	-30.43	-30.20	-3.64	-35.66
P VV	-18.21	-28.49	-48.89	-19.45	-29.96
P HV	-24.26	-34.38	-40.88	-24.81	



Figure D.5 Simplified woodland stand (Secondary Sampling Unit 148\_16) of Callitris glaucaphylla and Eucalyptus melanophloia.

Table D.5The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 148\_16).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-8.57	-10.31	0.00	0.00	-19.79
C VV	-6.50	-8.51	0.00	0.00	-17.44
C HV	-17.91	-17.91	0.00	0.00	
L HH	-13.28	-19.47	-20.07	-17.21	-23.73
L VV	-15.66	-18.73	-33.38	-30.99	-25.87
L HV	-28.72	-28.16	-34.11	-44.18	
P HH	-9.28	-20.33	-18.05	-10.44	-30.22
P VV	-14.24	-22.13	-27.89	-16.41	-25.58
P HV	-28.00	-30.04	-33.13	-39.64	



Figure D.6 Simplified woodland stand (Secondary Sampling Unit 23\_15) of Callitris glaucaphylla and Eucalyptus melanophloia.

Table D.6The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 23\_15).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-9.25	-10.66	-57.09	-53.60	-18.53
C VV	-6.56	-8.13	-70.21	-67.72	-16.07
C HV	-16.45	-16.45	-71.86	-86.93	
L HH	-9.87	-20.50	-24.14	-10.88	-27.28
L VV	-13.34	-19.15	-35.27	-19.13	-24.63
L HV	-28.15	-28.55	-41.84	-41.75	
P HH	-8.35	-12.61	-12.03	-15.81	-31.05
P VV	-9.59	-12.09	-25.96	-14.13	-27.17
P HV	-17.87	-18.24	-30.28	-34.15	



Figure D.7 Simplified woodland stand (Secondary Sampling Unit 144\_19) of Callitris glaucaphylla and Eucalyptus melanophloia.

Table D.7The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 144\_19).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-7.01	-11.86	-75.36	-64.61	-23.14
C VV	-5.67	-6.68	-88.00	-78.32	-21.13
C HV	-13.28	-13.28	-89.35	-91.20	
L HH	-14.64	-21.73	-23.19	-17.60	-21.69
L VV	-16.43	-19.76	-31.19	-33.47	-23.75
L HV	-28.64	-29.21	-38.94	-43.93	
P HH	-14.43	-25.40	-20.64	-16.30	-27.70
P VV	-18.93	-24.84	-31.93	-22.31	-28.89
P HV	-28.12	-29.55	-38.45	-35.41	



Figure D.8 Simplified woodland stand (Secondary Sampling Unit 142\_18) of Eucalyptus populnea.

Table D.8The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 142\_18).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-8.65	-9.04	-56.56	-54.47	-19.38
C VV	-23.26	-8.45	-65.12	-63.92	-15.24
C HV	-20.59	-20.59	-72.95	-104.99	
L HH	-11.08	-21.18	-21.93	-12.35	-22.32
L VV	-13.90	-20.78	-34.62	-19.54	-27.62
L HV	-29.52	-29.78	-43.75	-46.32	
P HH	-10.13	-37.24	-36.44	-10.21	-29.16
P VV	-14.46	-37.06	-50.50	-15.08	-23.40
P HV	-40.44	-45.00	-58.86	-42.41	



Figure D.9 Simplified woodland stand (Secondary Sampling Unit 58\_29) of Eucalyptus populnea and Eucalyptus melanophloia.

Table D.9The contribution of each scattering mechanism (dB) to the overallSAR backscatter at different frequencies and polarisations (Secondary Sampling<br/>Unit 58\_29).

	Total	Branch/	Branch	Trunk	Ground
		Foliage	Ground	Ground	
C HH	-7.21	-9.47	-76.07	-74.00	-11.08
C VV	-4.73	-7.65	-87.11	-85.06	-7.81
C HV	-17.26	-17.26	-92.27	-116.60	
L HH	-10.97	-17.80	-21.21	-13.80	-18.55
L VV	-11.79	-17.43	-30.12	-18.35	-14.95
L HV	-26.51	-27.15	-37.95	-38.77	
P HH	-10.51	-17.47	-15.35	-14.23	-23.23
P VV	-12.50	-16.85	-22.67	-17.94	-18.46
P HV	-20.98	-21.40	-31.86	-39.26	

## Appendix E



Figure E1 Legend describing woodland species and polarisation for the backscatter from various interactions at C-, L- and P-band, demonstrated in Figures E2-E10.



q

ට





q

ට

Backscatter (dB) (x-axis) from various interactions at C-, L- and P-band for Secondary Sampling Unit 114\_12 Figure E4





q

С С




ට

**a**)



Backscatter (dB) (x-axis) from various interactions at C-, L- and P-band for Secondary Sampling Unit 58\_29 Figure E9

a)

(q

ට



a)

## Appendix F











Figure F3 Simulated backscatter from the trunk component of the combined coniferous species

















Figure F8 Simulated backscatter from the trunk component of the combined eucalypt species







