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THE POTENTIAL OF SYNTHETIC APERTURE RADAR (SAR) FOR QUANTIFYING THE BIOMASS OF AUSTRALIA'S WOODLANDS

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Abstract

The potential of Synthetic Aperture Radar (SAR) for estimating the above ground and component biomass of woodlands in Australia is demonstrated using two case studies. Case Study I (Injune, central Queensland) shows that JERS-1 SAR L HH data can be related more to the trunk than the leaf and branch biomass of woodlands. A strong relationship between L HH and above ground biomass is obtained when low biomass pasture sites are included. Case Study II (Talwood, southern Queensland) determines that L and P band data can be related both to trunk and branch biomass, due to the similarity in the orientation and size of these scattering elements, and also to total above ground biomass. Saturation of the C, L and P band data occurred at approximately 20-30 Mg/ha, 60-80 Mg/ha and 80-100 Mg/ha. These preliminary results indicate that data from SAR are useful for quantifying changes in carbon stocks resulting from land use change in Australia's woodlands and for applications in rangeland assessment and management.

Key words: remote sensing, biomass, woodlands

Introduction

Australia's rangelands cover almost six million square kilometres, or 74%, of the continent's land surface and consist of a diverse range of ecosystem types including native grasslands, shrublands, woodlands and tropical savanna woodlands (James *et al.* 1999). Unsuited for cultivation, these rangelands represent an important source of forage for commercial livestock.

Within Australia, there is considerable concern regarding the sustainable development and well being of rangelands. In particular, extensive areas are being degraded as a result of accelerated soil erosion, soil salinity, overstocking and inappropriate fire, water and soil management practices (Stafford Smith and Morton 1990). Furthermore, there is an increase in the number and distributions of weeds and feral animals. Together, these factors are leading to reductions in biodiversity and even extinctions of plant and animal species. Of concern also, is that the clearance of rangeland vegetation, particularly woodlands, has increased in recent years to sustain or enhance agricultural productivity (Anderson *et al.* 1997). In particular, vegetation clearance has often been adopted as an investment strategy as, in many cases, beef production can be at least doubled following clearance and land values increase accordingly (Carter *et al.* 1998).

Since the 1990s, attention has focused on Australia's woodlands, as vegetation clearance is leading to substantial losses of terrestrial carbon to the atmosphere. In the recently revised 1990 National Greenhouse Gas Inventory (NGGI), which Australia is obliged to compile and update under the 1992 United Nations Framework Convention on Climate Change (UNFCCC), an estimated 90 million tonnes (Mt) of carbon dioxide equivalent (CO_2-e) were emitted through vegetation clearance. This emission represented approximately 23% of Australia's total 1990 emissions of 385 Mt CO_2-e. In 1996, emissions due to clearance had reduced to an estimated 63 Mt CO_2-e, or 15% of Australia's total emissions (419 Mt CO_2-e). This reduction was attributed partly to the provision of more reliable data on both the area and biomass of vegetation cleared and the dynamics of soil carbon as well as a genuine decrease in rates of vegetation clearance. However, the uncertainty associated with the data used to develop estimates of emissions and removals in the Land Use Change and Forestry sectors was still described as medium to high, ranging from 20 – 60% (Australian Greenhouse Office 1999).

The largest area of land cover change has occurred in Queensland. Although estimates of the area cleared of vegetation were calculated originally using extrapolations from non-spatial observations, the situation was later confirmed by comparing time-series of Landsat TM data over the entire Intensive Land Use Zone (ILZ) of Australia (Kitchen and Barson 1998, Bureau of Resource Sciences 1999). The ILZ, which covers approximately 2,984,000 km^2, or 39% of the Australian continent, represents the area that is under greatest threat from clearing (both actual and potential; Graetz *et al.* 1995). In the latest assessment for the period 1990 to 1995 (Table 1), 56% (1 million ha) of the total area of native woody vegetation clearance in Australia occurred in Queensland, with the majority (91.7%) cleared for grazing. Annual rates of vegetation clearance in this State averaged 268,060 ha, with 245,060 ha per year cleared for grazing. In contrast, the total area of regeneration was 127,230 ha over the period 1990 to 1995, with 89% occurring on grazing land.

Table 1. The decrease (hectares) in woody vegetation in the Intensive Land Use Zone of Australia for the nominal period 1990-1995 (Bureau of Resource Science 1999).

	Total area Cleared (ha)	% of total area cleared (%)	% of area cleared for grazing
ACT	4,590	0.3	0
New South Wales*	206,680	11.6	0
Northern Territory	16,510	0.9	6.5
Queensland	1,008,710	56.5	91.6
South Australia*	81,580	4.6	0
Tasmania	42,370	2.4	9.0
Victoria*	89,760	5.0	0
Western Australia*	334,000	18.7	0
TOTAL	1,784,200	100.0	0

* Area cleared for grazing not recorded

Despite the availability of these comprehensive land cover change datasets, the greenhouse gas emission estimates associated with land cover change remain largely uncertain due to the lack of spatial data on both the biomass (carbon content) of pre-cleared or pre-degraded vegetation and the biomass increment (carbon uptake) of regenerating vegetation. In addition, the contribution of vegetation thickening to overall emissions from land cover change, is uncertain. This process is commonplace in many of Queensland's woodlands. Caused by several factors, that include a reduction in fire frequency, thickening leads to an increase in vegetation density and both live and dead woody biomass. Recent estimates, although uncertain, suggest that vegetation thickening represents a carbon sink of approximately 100 Mt CO_2-e per year (Carter *et al.* 1998).

Due largely to Australia's commitments to international agreements aimed at reducing carbon emissions, such as the UNFCCC, the uncertainty in the estimates of carbon losses and gains associated with land use change needs to be addressed. In particular, there is a real need to develop operational techniques for spatially quantifying the biomass of pre-disturbed, degraded, regenerating and thickening vegetation. Although approaches to achieving this objective have been proposed, several of which are briefly outlined in this paper, most have not adequately considered the use of remotely sensed data. In particular, the use of airborne and spaceborne Synthetic Aperture Radar (SAR) for quantifying and mapping vegetation biomass, have not been investigated despite the success of studies internationally. The main aim of the paper, therefore, is to demonstrate, using two case studies in Queensland, the potential of SAR for quantifying the above ground biomass of woodlands in Australia.

Current approaches to estimating the biomass of Australia's forest and woodlands

A number of approaches to estimating the biomass of Australia's forests and woodlands have been proposed. The simplest has been to group classes within existing vegetation maps and to associate each group with the best available estimate of biomass. An alternative strategy has been to assign biomass estimates to vegetation distributions as modeled and mapped using biogeographic information, climate surfaces, soils data and, in some cases, remotely sensed data.

Some limitations to these approaches are apparent.

1. The maps generated are often lacking in consistency and inclusiveness of all vegetation types (Bergen *et al.* 1998).
2. Within mapped classes, the vegetation is often assumed to be in a mature state (and homogeneous in terms of structure, floristics and biomass) whereas, in reality, a range of regeneration and degradation stages may exist. The growth of vegetation at all stages of regeneration/degradation will also vary in response to local differences in soil, climate and land use.
3. 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.
4. Most biomass estimates are biased towards commercial forests, with many derived using timber volume and wood density estimates. In these cases, little consideration is given to the below ground and non-commercial components such as the leaves and branches.

An advancement on these approaches has been to model and map potential biomass using terrain-adjusted soils and climate surfaces and remotely sensed data as input to forest growth models (Landsberg and Waring 1997). Although demonstrating enormous potential, such approaches are currently restricted to relatively even-aged forests with closed canopies and have been difficult to validate due to the lack of appropriate ground data.

An approach that has been widely adopted in Australia has been to relate field estimates of biomass surrogates (e.g. basal area) to remotely sensed data from optical satellite sensors, such as the Landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR). For example, the Queensland Department of Natural Resources (QDNR) generated a multiple non-linear regression model that predicted tree basal area as a function of the Normalized Difference Vegetation Index (NDVI), calculated from AVHRR visible and near infrared data, and mean annual temperature, as derived from climate surfaces. Above and below ground biomass were then estimated for the Australian continent, and at 1 km spatial resolution, using this model and relationships established between biomass and stand basal area, as derived using data from published Australian studies (John Carter, pers. comm.). A similar approach was adopted by Kuhnell *et al.* (1998) whereby relationships between Foliage Projected Cover (FPC) and both Landsat TM NDVI and channel 5 mid infrared data were developed initially. FPC was then related to basal area and subsequently to biomass.

The acquisition and use of time-series Landsat sensor data for land cover change assessment by both Federal and State agencies has provided an incentive for focusing on these datasets for spatially quantifying biomass However, a recognised limitation of optical data is that the two-dimensional structure of vegetation is observed, and only indirect relationships with biomass may be obtained (Harrell *et al.* 1997).

Synthetic Aperture Radar (SAR): Potential for biomass estimation

Unlike optical sensors, that utilise energy from the sun, SAR is an active remote sensing system that generates its own energy source and is therefore independent of solar illumination.

The system can operate both day and night and the microwaves emitted penetrate through clouds thereby allowing all-weather viewing. 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. Characteristics of a radar system include wavelength, incidence angle and polarisation, all of which can be optimised to acquire information about the type of surface materials and 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 (wavelength of ~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 (e.g. Wang *et al.* 1994, 1995).

A number of studies have suggested that, due to the penetrative capacity of microwaves, the total above ground biomass of vegetation may be estimated using single polarised data. However, C, L and P band data have been shown to saturate (i.e. where the measured backscatter becomes insensitive to changes in biomass) at a biomass of approximately 20-40 Mg/ha, 60-100 Mg/ha and 150 Mg/ha respectively. However, by employing multi-band polarimetric data, the range of biomass detected by SAR may be extended. For example, by relating different SAR frequencies and polarisations to different components of the biomass, Dobson *et al.* (1996) and Kasischke *et al.* (1995) were able to estimate biomass up to 250 Mg/ha (± 16 Mg/ha) and 400 Mg/ha (± 80 Mg/ha) respectively. Other studies (e.g. Beaudoin *et al.* 1994, Harrell *et al.* 1997) have also indicated that polarimetric data may be used to better estimate the component biomass of vegetation.

Use of SAR in Australia

The majority of studies investigating the use of SAR data for biomass estimation have focused 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, Green 1998). A few studies have also concentrated on mixed forests in boreal (Fransson and Israelsson 1999), temperate (Bergen *et al.* 1998, Ranson *et al.* 1997) and tropical regions (Luckman *et al.* 1997, 1998, Foody *et al.* 1997).

In Australia, the use of both spaceborne and airborne SAR for quantifying forest biomass has not been investigated rigorously. This is despite the availability, since 1991, of data from a range of airborne and spaceborne SAR sensors. These include the European Earth Resources Satellites (ERS-1 and ERS-2) SAR, the Canadian RADARSAT, the Japanese Earth Resources Satellite (JERS-1)SAR, the Space Shuttle Imaging Radars (SIR-B and -C SAR)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 lack of adoption are proposed.

1. 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 and ground layer as well as the roughness and orientation of the terrain.
2. The few studies (Imhoff *et al.* 1997, Witte *et al.* 1998) that have investigated the use of SAR data have had limited success, due partly to the use of inappropriate surrogates for biomass (e.g. basal area) as ground data.
3. SAR data have only become widely available since the early 1990s but, until only recently,the Australian Centre for Remote Sensing (ACRES) has been unable to process the raw signal data acquired from spaceborne SAR.

The use of SAR data for estimating the biomass of Australia's vegetation should, however, be advocated for several reasons.

1. The majority (124 million ha) of Australia's 155 million ha of forested area is represented by woodlands, the biomass of which rarely exceeds 100 Mg/ha and is especially low in areas of regeneration. Therefore, the biomass of most woodland areas should be quantifiable using, as a minimum, single polarised L band data as most of the biomass is below the observed threshold of saturation.
2. A large proportion of the Australian continent receives little rainfall compared to many areas of the world and the moisture content of vegetation and soil, particularly in the dryer areas supporting woodland, is unlikely to vary substantially within regions and over time.
3. Much of the landscape is relatively flat and the influence of the terrain on the SAR backscatter is likely to be minimal.

Study sites

The following sections outline two case studies that provide a preliminary demonstration of the potential of SAR for estimating the biomass of woodland vegetation in Queensland. The first considers the use of JERS-1 SAR L HH (horizontally transmitted, horizontally received) data for quantifying the above ground biomass of woodlands near Injune, central Queensland. The second examines the use of NASA JPL AIRSAR polarimetric data for quantifying the above ground and component biomass (i.e. leaves, branches, trunks) of woodlands near Talwood, southern Queensland.

Natural vegetation and land use

Both sites are located in the Southern Brigalow Belt (SBB), a biogeographic region of southeast and central Queensland (Fig. 1). More than 50% of clearing in Queensland has occurred in the SBB, with over 40% occurring on freehold rather than leasehold land (Carter *et al.* 1998). Wholesale clearance of vegetation in the region has been extensive, due largely to the establishment of cattle pasture, the expansion of wheat farming and, more recently, the formation of cotton fields. Partial clearance of vegetation has also been commonplace in the pastoral areas, whereby most of the woody vegetation has been removed or poisoned whilst the herbaceous plants have been retained. Due to the complex nature of land use and management practices, the landscape consists of a mosaic of cleared fields and forest and woodland communities in various stages of degradation and/or regeneration.

Most of the SBB receives an annual average rainfall of between 500-750 mm, with between 60% and 70% occurring in the summer months from October to March. A detailed description of climate regimes, soil types and plant community composition for both sub-regions is provided by Neldner (1984). Within the Injune and Talwood regions, the gently undulating country supports white cypress pine (*Callitris glaucophylla*) stands on the sandy hills. The more alluvial clays in the valleys are dominated by *Eucalyptus* and *Acacia* woodlands, comprising mainly poplar box (*E. populnea*), silver-leaved ironbark (*E. melanaphloia*) and brigalow (*A. harpophylla*). Common understorey species include wilga (*Geijera parviflora*) and sandalwood Box (*Eremophila mitchelli*). At Talwood, C. *glaucophylla* is at the southern end of its range although belah (*Casuarina cristata*) is common.

Allometric equations for biomass estimation

For many species typical to both study sites, allometric equations relating measurements of tree size (e.g. height, diameter) to total above and component biomass were available to estimate stand biomass.

For the *Eucalyptus* species, *E. populnea*, *E. melanaphloia* and *E. crebra*, allometric equations were developed by Burrows *et al.* (1998) to estimate the biomass of different components, including the trunks, branches and leaves, from measurements of stem circumference at 30 cm. For a range of understorey genera, such as *G. pariflora and E. mitchelli*, equations were derived by Harrington (1979) to estimate both wood (branch, trunk and bark) and foliage biomass from measurements of tree diameter (at 30 cm) and/or tree height (m). Both studies advocated the use of a bias correction factor (bcf), calculated as the antilog of one half of the sample variance (i.e. the standard error of the estimate squared), to avoid systematic bias when antilogging estimates to arithmetic units (Baskerville 1972, Beauchamp and Olson 1973)

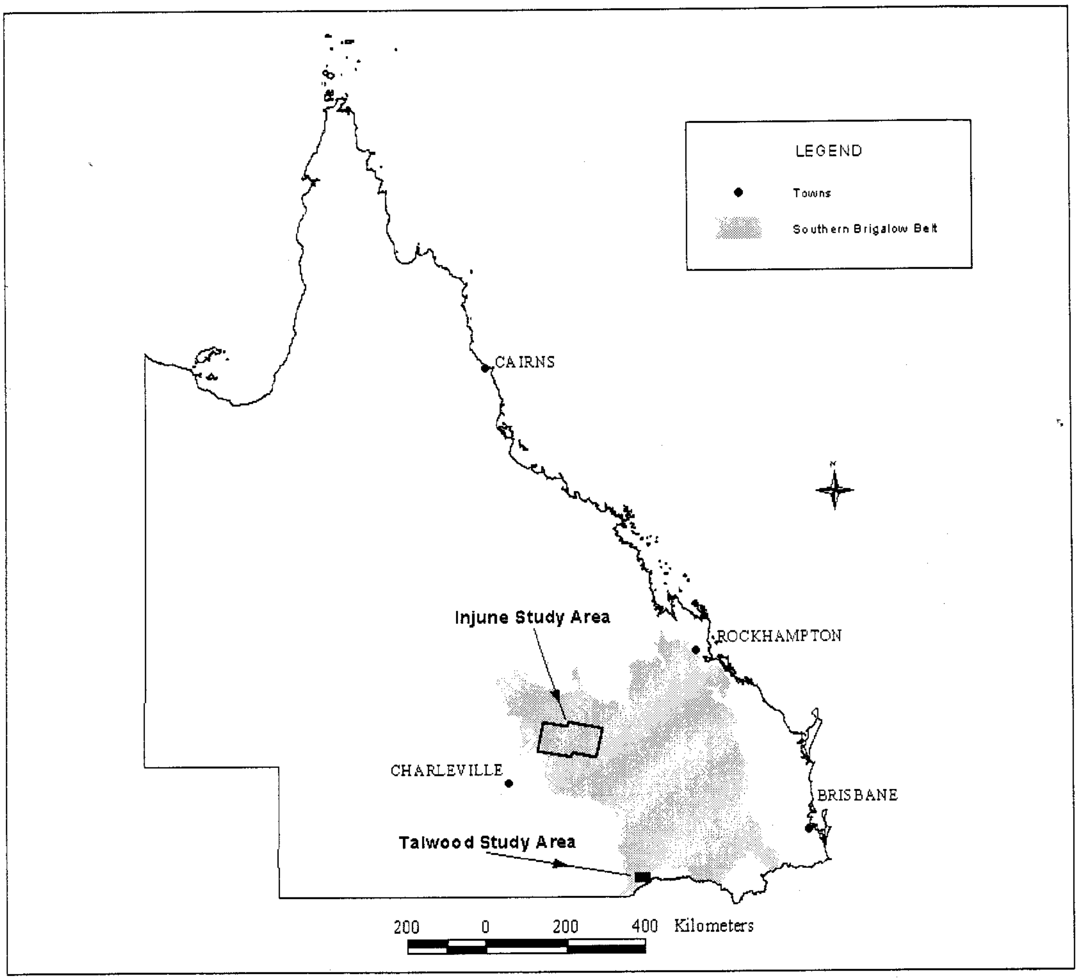

Fig. 1. Location of the Southern Brigalow Belt and the Injune and Talwood study areas.

Comprehensive allometric equations for biomass estimation had not been generated in Australia for the coniferous *species C. cristata* or *C. glaucophylla*. The only available equations that estimated the component biomass of *C. cristata* were based on young plantations in China (Tsair and Chin 1988). For *C. glaucophylla*, only volume equations and relationships between diameter at breast height (130 cm) and height were available. These were generated by State Forests of New South Wales and the Queensland Department of Primary Industries (QDPI) Forestry Department respectively. The estimation of stem biomass required multiplication of stem volume by wood density (Boland *et al.* 1984). Estimation of leaf and branch biomass could only be achieved using ratios established with like-species (i.e. *C. cristata*).

Case Study I: Injune

Field data collection and estimation of stand biomass

In July 1997, field data were collected from 52 plots located in a range of disturbance and regeneration classes within the major woodland types. The selection of sample sites was based largely on existing vegetation mapping and descriptions (Neldner 1984). Landsat TM and aerial photographs were also used to delineate broad forest types and growth stages and to assess structural homogeneity within the delineated stands. An additional eight sites representing pasture were also identified.

At each of the 52 sample sites, data on individual species and diameter at 1.3 m were recorded using the prism sweep method (Beers and Miller 1965, Dilworth and Bell 1971). The method uses a critical angle from a central location to determine the inclusion or exclusion of individual trees within the sample. The critical angle is determined using wedge prisms of variable size. The Global Positioning System (GPS) coordinates of the centre of each sweep (up to five per site) were also obtained with an accuracy of ± 10 metres.

Using the allometric equations outlined above, the above ground and component (leaf, branch and trunk) was estimated for each plot. The subsequent scaling up of the measurements to a per hectare basis was based on the assumption that each tree selected within each plot had the same basal area and component biomass per unit area (Dilworth and Bell 1971).

Acquisition and processing of remotely sensed data

For the study area, a 1995 Landsat TM channel 3 (red), 4 (near infrared) and 5 (mid infrared) image, acquired through the SLATS (Statewide Land Cover and Trees) project, was georeferenced to Australian Map Grid (AMG) coordinates using control points located with differential GPS (Collett *et al.* 1998, Kuhnell *et al.* 1998). Two overlapping JERS-1 SAR L HH scenes were acquired for August and September, 1994, and were each registered to the Landsat TM data using ground control points (GCPs) located in both images. The root mean square (r.m.s) errors for all transformations were within ± 1 pixel and the resampled pixel size for the JERS-1 SAR data was 25 m. The JERS-1 SAR data were calibrated to the backscatter coefficient (σ^0), defined as the average radar cross section per unit area of the individual scattering elements. For display purposes, σ^0 was expressed in decibels (dB). Speckle suppression within the JERS-1 SAR data was based on consecutive applications of a 3 x 3 Lee Sigma, a 5 x 5 Lee Sigma and a 5 x 5 Local Region Filter. These adaptive filters used the standard deviations of pixels within the n x n window to determine a new pixel value, and were applied to remove speckle noise which is characteristics of most SAR data.

For each of the 52 sites, and using the GPS coordinates for each of the sweep centres, a polygon was produced by connecting the centre coordinates and buffering the joining lines by 50 metres. The actual distance from the sweep centre of trees that were included for measurement depended upon the size of the prism used and the diameter of the individual stems. However, a distance of 50 metres ensured that the majority of trees fell within the polygon. As most sites were located well within particular woodland classes, there was a minimal chance of overlap in the area represented by each polygon and adjacent woodland classes. For each of the 52 polygons generated, the average (and standard deviation) JERS-1 SAR σ^0 data values were extracted and related to the estimates of total and component biomass.

Results

The estimates of total above ground biomass ranged from 34 Mg/hato 156 Mg/ha,with a mean biomass of 71.5 ± 29.9 Mg/ha. The larger estimates of biomass were associated with woodlands dominated by *C. glaucophylla*. As younger regrowth was not measured, the range of biomass from 0 to 34 Mg/ha was not represented, although a number of locations representing pasture were identified.

L HH data values for woodland areas ranged from –7 to –15 dB. Where pasture sites were excluded, relationships between L HH and both leaf and branch biomass were barely significant with coefficient of determination (r^2) values of 0.09 in both cases (Table 2; Fig. 2). By including pasture sites, the r^2 values defining the relationship between LHH and leaf and branch biomass increased to 0.26 and 0.53 respectively. The strongest relationship was observed between L HH and trunk biomass, with r^2 values of 0.49 without pasture sites and 0.67 with pasture sites. The strength of the relationships between L HH and both stem (trunk and branch) and above ground (trunk, branch and leaf) was lower. A stronger relationship between L HH and above ground biomass was, however, observed (r^2 = 0.62) when pasture sites were included, although saturation occurred at an above ground biomass of approximately 60-80 Mg/ha.

Table 2. Relationships between L HH (dB) and the log of component biomass, without and with pasture sites ($p < 0.001$) expressed on the basis of the coefficient of determination (r^2)

Biomass component	Without pasture (r^2)	With pasture (r^2)
leaf	0.09	0.26
branch	0.09	0.53
trunk	0.49	0.67
stem	0.35	0.61
ground biomass	0.34	0.62

Case Study II: Talwood

Field data collection

In October, 1998, field data were collected from 29 fixed and variable area plots sited in woodlands at varying states of degradation and/or regeneration. The GPS coordinates of the centre of each plot were obtained with an accuracy of ± 10 metres. Fixed area plots were preferentially established in areas of younger regeneration. All trees < 3 cm in diameter were identified to species, counted and their height estimated. Variable area plots, sampled using the prism wedge method, were established in the older regenerating woodlands and in intact, albeit degraded, woodlands where fixed area plots were considered to be overly time-consuming. Within these plots, all included trees were identified to species and the diameters at both 30 cm and 130 cm were recorded. For the understorey species *E. mitchelli* and *G. parviflora*, relationships were established between tree height and diameter (at 30 cm), as both parameters could be used as input to the equations of Harrington (1979). For all trees, the component biomass was estimated using the allometric equations outlined above and scaled up to a per hectare basis using standard procedures (Dilworth and Bell 1971).

Acquisition and pre-processing of remotely sensed data

On the 12 November 1996, AIRSAR data were acquired over a 10 x 60 km strip of the study area. In this overflight, AIRSAR topographic and interferometric SAR (TOPSAR) data were acquired for the generation of digital elevation models (DEMs). TOPSAR data are effectively polarimetric SAR with the horizontal components used to generate DEMs, leaving only single polarised C VV and L VV and polarimetric P band (HH, VV and HV) available for analysis.

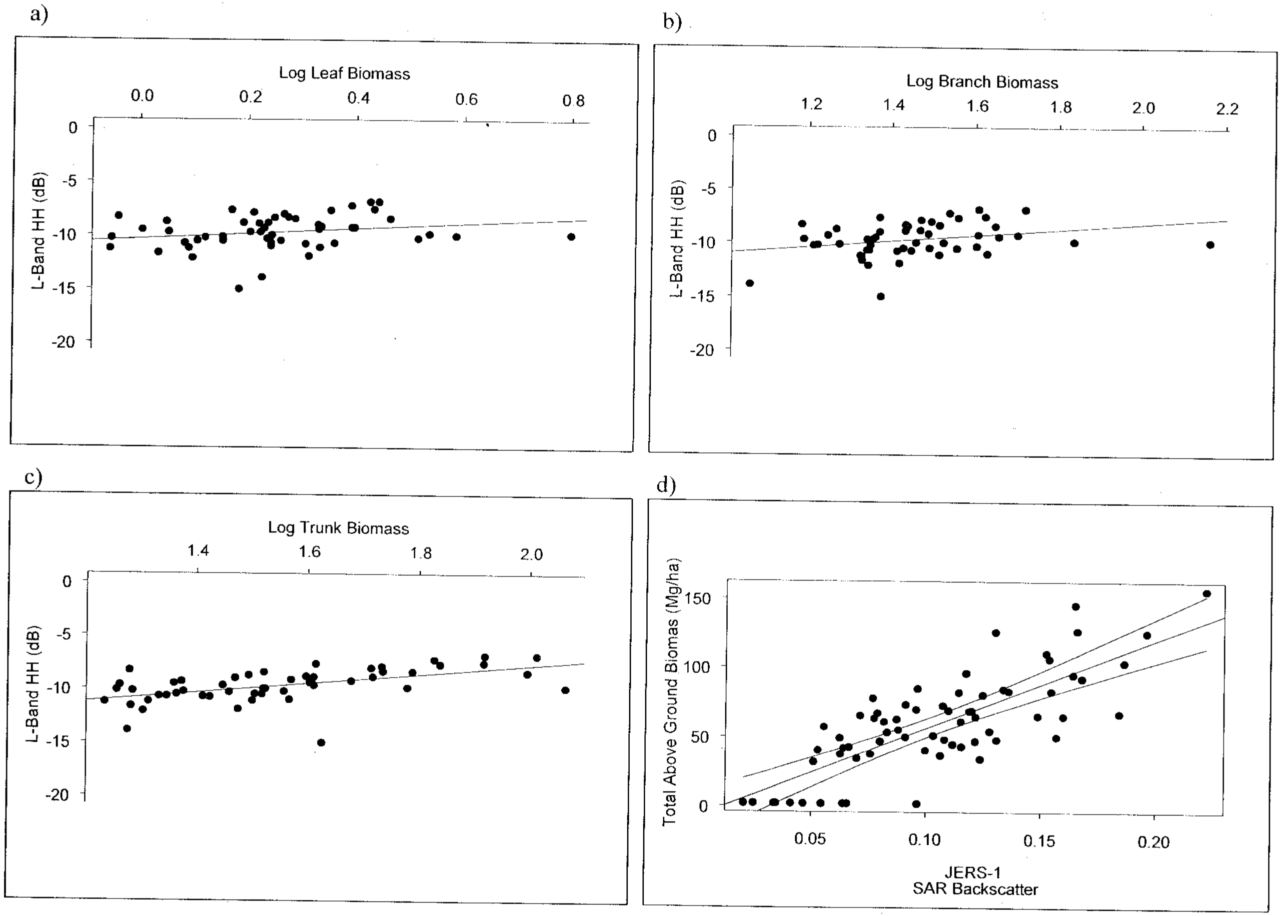

Fig. 2. Relationships between JERS-1 band HH (σ^o dB) and (a) leaf biomass, (b) branch biomass, and (c) trunk biomass (without pasture sites). The relationship between L HH σ^o (m^2/m^2) with total above ground biomass (including pasture sites) is shown in (d).

Landsat TM data of the sub-region had been acquired previously for July, 1995, through the Statewide Landcover And Trees Study (SLATS; Queensland Department of Natural Resources 1997) and were georeferenced to AMG coordinates. The AIRSAR image was then registered to the Landsat TM data using GCPs located in both images and resampled, using a nearest neighbour algorithm, to a pixel resolution of 12.5 metres. The AIRSAR C, L and P band intensity data were calibrated to the backscatter coefficient (σ^o).

Results

For the Talwood site, the above ground biomass ranged from 22 Mg/ha (young regenerating woodlands) to 138 Mg/ha (mature *C. cristata* woodlands) with a mean biomass of 57 Mg/ha Pasture sites were assumed to support no woody biomass and a leaf biomass of 1 Mg/ha.

Relationships between σ^o and component biomass were established by first extracting C VV, L VV and multipolarimetric P band data from a 3 x 3 pixel window centred on each plot location and second, establishing a linear regression between the log of σ^o (dB) and the log of component biomass. The r^2 values for the regression are shown in Table 3 whilst selected relationships between C VV σ^o and leaf biomass, L VV σ^o and branch biomass, and P HH σ^o and both branch and trunk biomass are illustrated in Fig. 3. The relationships established included data for low biomass pastures.

Table 3. Relationship between C, L and P band σ^o and component biomass, expressed on the basis of the coefficient of determination (r^2).

	SAR backscatter coefficient (dB)					
	PHH	PVV	PHV	PTP	LVV	CHH
Log Branch	0.85	0.80	0.83	0.84	0.83	0.64
Log Trunk	0.81	0.75	0.80	0.80	0.78	0.55
Log Leaf	0.36	0.33	0.35	0.36	0.41	0.46
Log Total	0.91	0.83	0.91	0.89	0.88	0.69

The strongest relationship with leaf biomass was obtained using C VV data, with backscatter ranging from –12 to –20 dB. The relationship was similar, although slightly weaker, with L VV data (range –27 to –45 dB) and was least with P band data (all polarisations). The relationship with branch biomass was relatively weak using C VV data but was of similar magnitude for both L VV and P band (all polarisations), with r^2 ranging from 0.80 to 0.85. C VV was least related to the trunk biomass whilst a strong relationship ($r^2 > 0.75$) was observed using both L VV and P band data.

Significant relationships, at the 95% confidence level, between above ground biomass and σ^o (dB) at all wavebands and polarisations was observed, although the strongest relationship ($r^2 = 0.91$) was observed using P HV and P HH data. However, the range of values for P HV was 27.4 (–18.5 to - 45.9 dB) which was far greater than the range for P HH and VV which was 22.57 (-9.56 to –32.1 dB) and –18.8 (-12.0 to –30.8) respectively. Saturation of the C, L and P band data occurred at approximately 20-30 Mg/ha, 60-80 Mg/ha and 80-100 Mg/ha.

Discussion

The following sections examine the relationships observed between JERS-1 SAR and AIRSAR data and component biomass and assess the use of the data for above ground biomass estimation. The utility of allometric equations for providing ground estimates of woodland biomass is also discussed.

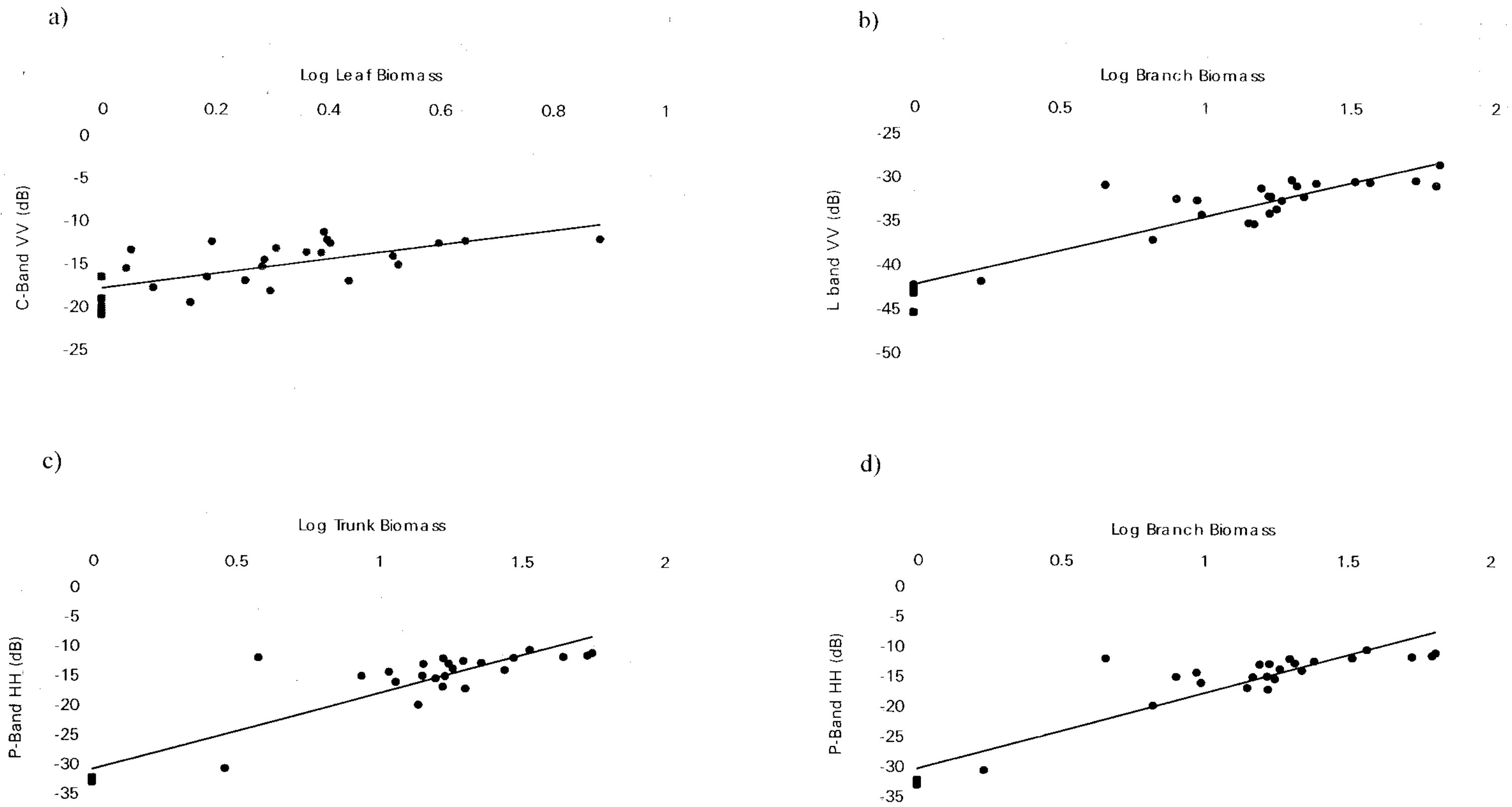

Fig. 3. Relationships between a) C band VV and leaf biomass, b) L band VV and branch biomass, c) P band HH and trunk biomass and d) P band HH and branch biomass, Talwood study region. (Pasture sites ■ woodland plots ●)

JERS-1 SAR for biomass estimation

The relationships established between JERS-1 L 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. For example, Fransson and Israelsson (1999) reported high sensitivity of JERS-1 L HH data to trunk biomass, whilst Wang *et al.* (1994) concluded that L HH backscatter was mainly a result of interaction between the trunk and the ground. However, Sieber (1995) reported that L HH microwaves penetrated through the leaves and interacted largely with the branches of trees. These conflicting results indicate that the interaction of L HH will vary depending upon the overall structure of the forest or woodland and, in particular, the differing sizes and orientation of trunks and branches. 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.

The study suggests that L HH is related only partially to above ground biomass and, at Injune, is best used to estimate trunk biomass. It is worth noting that several studies (Sader 1987, Wang *et al.* 1994) have indicated that, by using cross polarized L HV data or ratios of cross and like polarisations, better relationships with canopy biomass and angular orientation properties may be obtained. These studies suggest that polarimetric L band SAR may be of more value for spatially quantifying vegetation biomass, as both the trunk and canopy biomass may be estimated separately using L HH and L HV respectively. 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 showed that L HH 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 HH return became asymptotic at approximately 80 – 100 Mg/ha which may restrict the use of JERS-1 SAR to lower biomass woodlands. This saturation level compares favourably with the asymptotes of 100 Mg/ha observed using airborne Convair 990 SAR L HV, HH and VV data (Sader 1987), 60-100 Mg/ha observed using both JERS-1 SAR L HH and SIR-C SAR L HV/HH data of tropical regenerating forests (Luckman *et al.* 1997), and 70-80 Mg/ha using JERS-1 SAR L HH data (Fransson and Israelsson 1999).

AIRSAR TOPSAR data for biomass estimation

Although AIRSAR data of the Talwood site were acquired in 1996, many of the woodland sites from which field data were collected in 1998 had not been disturbed in the intervening period. Changes in biomass may have taken place over the 18 month period, but were considered to be relatively minor.

The range of total biomass observed at Talwood was typical for woodlands of the SBB although the higher biomass *C. glaucophylla* woodlands found at Injune were less common. Pasture sites were used to formulate the relationships in this study. However, further field data are needed for these sites to better define the relationship between SAR backscatter and above ground biomass over the range 1 – 10 Mg/ha.

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 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. In a study of hardwood-boreal transitional forests, Ranson *et al.* (1997) suggested that when the above ground biomass exceeded about 10 Mg/ha, C-band backscatter was dictated largely by tree crowns and the influence of other factors (e.g. soil moisture) was reduced. However, given the openness of Eucalyptus woodlands in Australia, it seems likely that the ground surface may contribute significantly to the C-band backscatter at all stages of regeneration, including the mature state. The better relationship between C 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. These observations stress the importance of understanding within-stand relationships between biomass components when attempting to understand the interaction of microwaves with vegetated surfaces (Green 1998).

Microwaves at both L 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*. To support this argument, Fig. 4 demonstrates that the woody biomass of woodlands at Talwood was divided approximately equally between the trunks and the branches. Compared to the JERS-1 SAR HH data for Injune, the AIRSAR L 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.

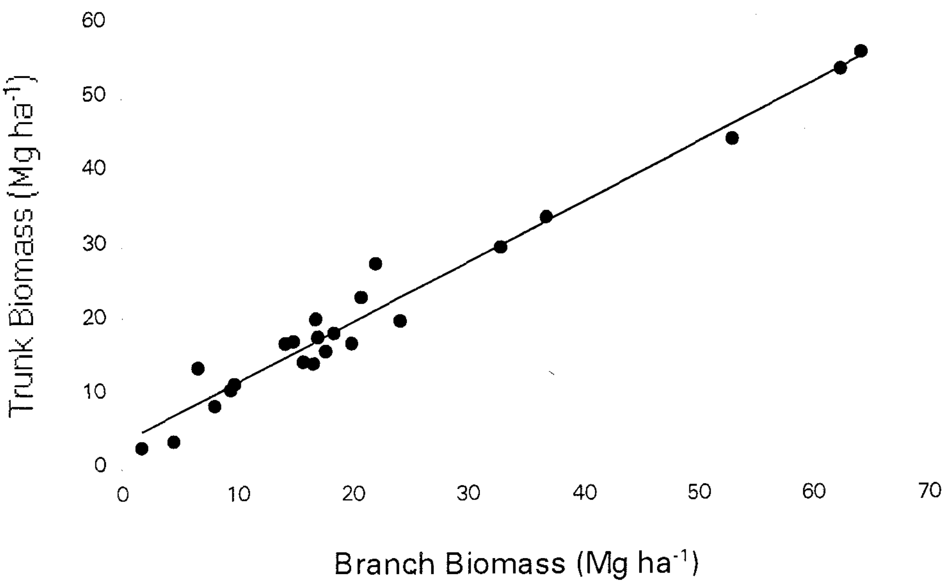

Fig. 4. The relationship between branch and trunk biomass for 28 woodland plots located near Talwood.

Differences in the P-band return at the three polarisations were not noticeable. In a study by Wang *et al.* (1994), P HH backscatter was largely from the trunk and the ground, suggesting that this polarisation was useful for estimating the biomass of coniferous forests where most of the biomass is contained within the trunk. In contrast, P HV backscatter was dominated by volume scattering within the canopy inferring that these data may be related to canopy biomass. Beaudoin *et al* (1994) also noted that P band was found to be the optimal frequency band for forest observations, with P HH returns related physically to both the trunk and crown biomass, whereas P VV and P HV returns were linked more closely to crown biomass. In this study, similar relationships using P band data were probably not observed due to the lack of layering within the uneven-aged woodland community.

In quantifying total above ground biomass at Talwood, a reasonable estimate may be obtained using either L or P band data. However, the dynamic range was greatest using P HV, suggesting that this polarisation may be optimal for maximising above ground biomass classes. P band data also saturates at a higher biomass compared to L band (80-100 Mg/ha) data, suggesting that these data are most suited for estimating the above ground biomass of woodlands in Australia. However, as the above ground biomass of some woodlands may exceed 150 Mg/ha, the combination of both L band and P band polarimetric data for estimating separate components of the biomass may be the best approach to quantifying biomass.

Characterisation of woodlands using allometric equations

Considering the low timber value of these woodlands, a range of allometric equations were available that were sufficient to estimate the biomass of both the overstorey and understorey vegetation at both Injune and Talwood. The allometric equations of Harrington (1979) and Burrows *et al.* (1998) were particularly useful in that the biomass could be confidently separated into different components, thereby allowing relationships with different SAR wavelengths and polarisations to be determined. The equations for *C. glaucophylla* were considered to be the most unreliable as no terms for estimating leaf and branch biomass were available. The equations for *C. cristata* were also considered less reliable as they were derived from young plantations in China.

Further limitations to the use of these equations were identified as follows:

1. All equations were derived originally from single stemmed individuals but, within many plots, multi-stemmed trees were commonplace, leading to uncertainties as to the best application of the equations.
2. The equations were established by harvesting trees at locations several hundred kilometres from where they were applied. As the form of the species was likely to differ as a result of changes in growth environments between the harvesting and measuring sites, an overestimate or underestimate of vegetation biomass can be expected.
3. The estimates of leaf biomass were likely to be in error due to differences in the phenological state of the vegetation at the times of harvesting and observation by SAR.

In order to establish reliable relationships between SAR backscatter and component biomass, allometric equations ideally need to be derived at the same time as the SAR overpass. In central Queensland, similar allometric equations were derived for several *Eucalpytus* species by Burrows *et al.* (1998). This result indicates that only a few generic species may need to be harvested to generate allometric equations that are representative of a particular site. Furthermore, harvesting of these same key species along environmental gradients may allow formulation of generalised allometric equations that are applicable across the region and could be used for large area survey in support of SAR data calibration and validation.

Conclusions and future work

The case studies reported in this paper are unique in that, for the first time in Australia, the potential use of both single band and multi-band polarimetric SAR for quantifying the above ground and component biomass of woodlands has been demonstrated. Using JERS-1 SAR and AIRSAR data for woodland sites in south and central Queensland, the study has demonstrated that:

JERS-1 L HH backscatter was related more to the trunk biomass, but provided limited information on branch and leaf biomass. This was attributed to the greater occurrence of the conifer *C. glaucophylla* at Injune.

1. A strong relationship between L HH and above ground biomass was obtained when low biomass pasture sites were included.
2. AIRSAR L VV and P band backscatter (all polarisations) from woodlands were related to both trunk and branch biomass, due largely to the similarity in the size distribution and orientation of these components.
3. AIRSAR C band backscatter may be related to leaf biomass, although time and site specific measurements of leaf biomass, that were coincident with a SAR overpass, would be required to confirm this relationship.
4. Saturation of C, L and P band data occurred at approximately 20-30 Mg/ha, 60-80 Mg/ha and 80-100 Mg/ha.

The biomass of woodlands in Australia may exceed 150 Mg/ha and the establishment of relationships between different components of the biomass and C, L and P band data may be necessary to estimate biomass with confidence. However, as much of the vegetation cleared is of low biomass (Burrows 1990), the use of L band data alone may be sufficient, although other polarisations other than L HH (i.e. L HV) may be required.

Further research should be aimed at obtaining a better understanding the interaction of microwaves of different length and polarisation with components of vegetation canopies, determining the influence of the ground layer, and assessing the consistency of relationships between and within sites and using different airborne and spaceborne sensors. The synergistic use of optical data for estimating leaf biomass should also be investigated.

In mid-2000, AIRSAR POLSAR and TOPSAR data will again be acquired at sites across Australia and, under an Australian Research Council (ARC) grant, site and time specific estimates of vegetation biomass will be obtained for Injune. This study will therefore allow the use of polarimetric C, L and P band data, and also SAR interferometry, for quantifying both the biomass and structure of the biomass of Australia's woodlands to be further investigated. From the early 2000s, also, the spaceborne ENVISAT Advanced SAR (ASAR) and the_Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) are scheduled for launch and will be acquiring polarimetric data at C and L band respectively. The ARC study will therefore provide some insight into the most suitable sensors for spatially estimating biomass on a regional basis.

In closing, it is hoped that the study encourages State and Federal agencies to re-examine the potential of SAR data for rangeland assessment and management and for better understanding the carbon dynamics of Australia's woodlands.

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