

FOREST AND WOODLAND BIOMASS AND CLASSIFICATION USING AIRBORNE AND SPACEBORNE RADAR DATA

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ABSTRACT

Global carbon emissions leading to change in climate and ecology systems have prompted the international community to establish a series of agreements aimed at reducing such emission. Australia as a signatory country to the 1997 Kyoto Protocol, is currently establishing a National Carbon Accounting System, to estimate and monitor carbon emissions from all major sectors. Forest and woodland biomass mapping, using remotely sensed data, can provide a unique, efficient and reliable assessment for biomass stocks and changes. Studies internationally have recognised that, among all the remote sensing technologies, SAR has the greatest potential to quantify biomass and structural diversity because of its ability of penetration.

While SAR data are promising for biomass mapping, SAR image classification based on pixel-analysis suffers from the existing speckle problem. It has been suggested that the SAR data analysis be best based on area-analysis. Segmentation is the process of partitioning an image into uniform areas and providing a base for area-analysis. In this paper, a segmentation method using the Gaussian Markov random field model, developed by authors in recent years is used to segment SAR images.

Several field campaigns have been conducted to collect ground truth data. Various sampling methods are used. In a detailed sampling method, all trees with a diameter at breast height (DBH) greater than 3 centimeters in a plot are counted, while the prism wedge technique uses a critical angle from a central location to include or exclude individual trees in a plot. The field data are then analysed and processed. Allometric equations permit the derivation of tree component biomass from a knowledge of tree species and diameters, as well soil and climate conditions. Biomass of branches, stems, trunks, foliages were all determined. These data serves benchmarks in image classification and accuracy assessments.

The accuracy of the classification is assessed using the collected ground truth data. Limitations of single polarisation data and advantages of multipolarisation and multiband data in terms of biomass mapping are addressed.

1. INTRODUCTION

Australian eucalypt species are not well characterised in terms of biometric models which allow the relative components of green foliage and woody biomass to be determined or to be predicted reliably. In forest and woodland analysis there is a strong reliance on developing better field based measurements. Also, as a result of the Kyoto Protocol and Australia's commitment to meet carbon emission levels under the UN Framework Convention on Climatic change, there is an increasing need to develop spatial extrapolation procedures that provide accurate estimates at both the local and regional level of changes in vegetation cover.

The potential of SAR to map the distribution of forests and woodlands and to monitor long term developments in these ecosystems, as well as to contribute to an understanding of global change, depends on the ability to unravel the

relationships that exist between the microwave backscatter of the return signal and the physical characteristics of trees and forests.

To use the radar parameters of wavelength, polarisation, phase difference and incidence angle to maximum effect to discern differences within forest environments, backscatter and linking models need to be developed that allow the biophysical properties of trees to be determined. In respect to temporal studies, such models must not only take into account structural components such as tree height, trunk diameter, branching pattern and canopy characteristics, but also incorporate the impact of changing environmental conditions such as prolonged wet and dry periods and the impact of stress caused by factors such as disease, fire and human interference, and the underlying slope of the land surface.

The first established empirically based relationships between radar backscatter and field measurements of selected tree parameters in tropical Australian forests that demonstrated multi-polarimetric SAR responds to differences in vegetation structure (eg. total biomass, leaf-area index, branch surface/volume ratio etc.) in predictable ways were presented by Imhoff *et al.*, (1997). These results showed radar sensitivity to floristically induced structural changes, indicating that given appropriate algorithms, the physiognomic classifications of trees and community typology might be possible with radar. Also, in associated research at the same site the vegetation structural changes identified in the radar analysis were shown to be significantly related to avian habitat quality thereby demonstrating the potential of SAR for studying biodiversity and habitat change.

More recent work reported in this paper shows a direct relationship between total above ground biomass and SAR backscatter for two sites in Queensland. At Injune in Central Queensland, a significant non-linear correlation between trunk biomass and JERS-1 single band SAR data was obtained with an r^2 statistic of 0.72. Strong relationships between multi-band SAR data and component biomass (ie branch, trunk, leaf and total biomass) were recorded for eucalypt woodland sites at Talwood in Southern Queensland. Here r^2 values of 0.91 were obtained for P-band SAR and total biomass.

The ability to derive estimates of tree stand parameters directly from SAR depends on the development of inversion models that facilitate prediction based on radar scattering characteristics alone and which include a means of extrapolating tree characteristics to areal measurements. The correlative relationships referred to above between biomass and floristic induced structural changes and radar backscatter have been analysed using wavelet transform techniques to suppress speckle noise in the imagery and a segmentation routine based on a Gaussian Markov Random Field Model has been developed to classify and spatially extrapolate the distribution of different stand densities and land cover types. These techniques are described in this paper in relation to their application to the Injune and Talwood study sites.

2. SAR AND BIOMASS ESTIMATION

A number of studies suggest that, due to the penetrative capacity of microwaves, the total biomass of vegetation may be estimated using single polarized data, although C, L and P band data have been shown to saturate at a biomass of approximately 20-40 Mg ha⁻¹, 60-100 Mg ha⁻¹ and 150 Mg ha⁻¹ respectively. However, by employing multi-band polarimetric data, the range of biomass detected by SAR can be extended. For example, by relating different SAR frequencies and polarisations to different components of the biomass, Dobson *et al.* (1995) and Kasischke *et al.* (1995) were able to estimate biomass up to 250 Mg ha⁻¹ (± 16 Mg ha⁻¹) and 400 Mg ha⁻¹ (± 80 Mg ha⁻¹) respectively. Other studies (e.g., Beaudoin *et al.*, 1994; Harrell *et al.*, 1997) have also indicated that polarimetric data may be used to estimate the component biomass of vegetation.

3. 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, 1997, Wang *et al.*, 1994; 1995, Harrell *et al.*, 1997; Baker *et al.*, 1994, and Green, 1998). A few studies have also concentrated on mixed forests in boreal (Fransson and Israelsson, 1999), temperate (e.g, Bergen *et al.*, 1998; Ranson *et al.*, 1997) and tropical regions (Luckman *et al.*, 1997; Foody *et al.*, 1998).

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. These include 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.

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

- 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^{-1} 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 threshold of saturation.
- A large proportion of the Australian continent receives little rainfall compared to many regions of the world and the moisture content of vegetation and soil, particularly in the dryer areas supporting woodland, is unlikely to vary substantially.
- Much of the landscape is relatively flat and the influence of the terrain on the SAR backscatter is likely to be minimal.

4. KAKADU WORLD HERITAGE REGION

The analysis of P-, L-, and C- band SAR data collected during the first NASA/JPL AIRSAR Campaign in Australia in 1993 over a section of the South Alligator River in Kakadu demonstrated the usefulness of SAR in identifying changes in woodland vegetation types occasioned by both structural and floristic differences. Statistically significant changes were evident where (1) a melaleuca woodland changed in structure from a tall, closed canopy to a more densely stocked formation of smaller trees of the same species, and (2) where the melaleuca were replaced by a mixed eucalypt woodland that characterises the drier uplands of Kakadu National Park. The best correlations between bole biomass and surface area/volume ratios were achieved between C-HV, L-VV, P-VV, C-VV, L-VV and P-VV respectively (Imhoff et al 1997).

5. QUEENSLAND STUDY SITES

The following sections outline two recent case studies that provide further demonstration of the use of SAR for estimating the biomass of Australian woodland vegetation. The first considers the use of JERS-1, L band HH data for quantifying the biomass of woodlands near Injune, in Central Queensland. The second examines the use of NASA JPL AIRSAR polarimetric data for quantifying the component biomass (i.e., leaves, branches, trunks) of woodlands near Talwood, Southern Queensland.

5.1 Natural Vegetation and Land Use

Both sites are located in the Southern Brigalow Belt (SBB), a biogeographic region of southeast and central Queensland (Figure 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 the 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.*

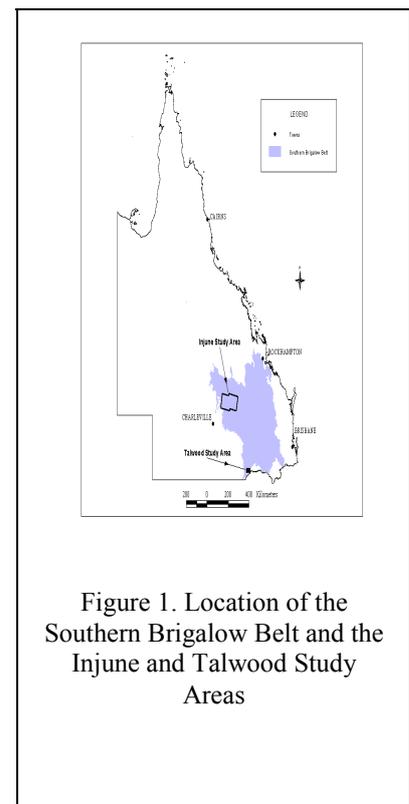


Figure 1. Location of the Southern Brigalow Belt and the Injune and Talwood Study Areas

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.

6. CASE STUDY I: INJUNE

6.1 Field Data Collection and Estimation of Stand Biomass

In July, 1997, field data were collected from 70 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.

At each of the 70 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 GPS coordinates of the centre of each sweep (up to five per site) were also obtained with an accuracy of ± 10 metres.

For each plot, and using the allometric equations outlined above, the above ground and component (leaf, branch and trunk) was estimated. 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).

6.2 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 AMG coordinates using control points located with differential Global Positioning Systems (Collett *et al.*, 1998; Kuhnell *et al.*, 1998). Two overlapping JERS-1 L channel 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 data was 25 m. The JERS-1 data were calibrated to the backscatter coefficient (σ^0 , $m^2 m^{-2}$), 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 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.

For each of the 70 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 are included for measurement depended upon the size of the prism used and the diameter of the individual stems. 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 between the created polygon and adjacent woodland classes. For each of the 70 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.

6.3 Results

The estimates of total above ground biomass ranged from 34 Mg ha⁻¹ to 156 Mg ha⁻¹, with a mean biomass of 71.5 \pm 29.9 Mg ha⁻¹. 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⁻¹ was not represented, although a number of locations representing pasture were identified.

L HH 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 r^2 values of 0.09 in both cases (Table 1; Figure 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. Relationships between L HH and both stem (trunk and branch) and above ground (trunk, branch and leaf) were low. A strong 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 80 Mg ha^{-1} .

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

Table 1. Relationship(r^2) between L HH (dB) and the log of component biomass, without and with pasture sites ($p < 0.001$)

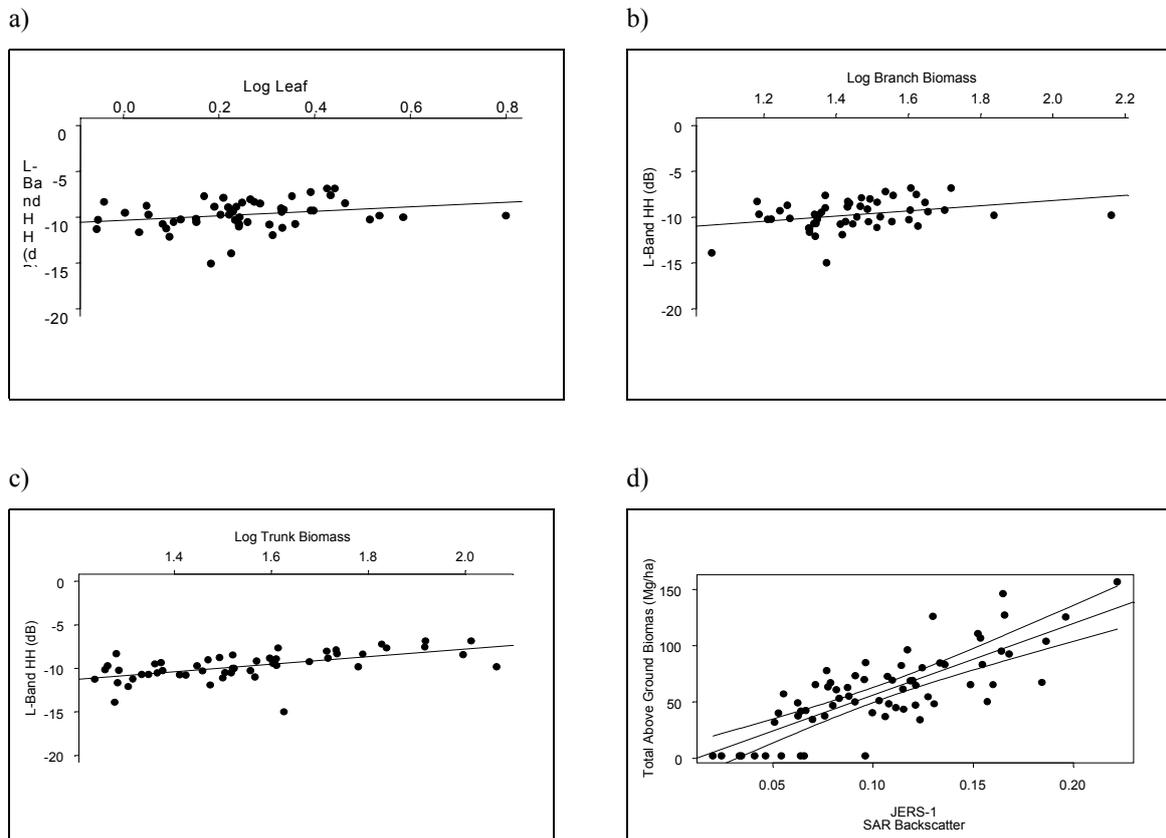


Figure 2. Relationships between JERS-1 L band HH (σ° dB) and (a) leaf biomass, (b) branch biomass, and (c) trunk biomass (without pasture sites). The relationship between L HH σ° ($\text{m}^2 \text{ m}^{-2}$) with total above ground biomass (including pasture sites) is shown in (d).

7. CASE STUDY II: TALWOOD

7.1 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 sweep (up to five per site) 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 the 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).

7.2 Acquisition and Pre-processing of Remotely Sensed Data

On the 12th 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.

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^0 , $m^2 m^{-2}$). Speckle was removed from all SAR data by applying a 3 x 3 Lee Sigma, 5 x 5 Lee Sigma and a 5 x 5 Local Region Filter.

7.3 Results

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

Relationships between σ^0 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^0 (dB) and the log of component biomass. The r^2 values for the regression are shown in Table 2 whilst selected relationships between C VV σ^0 and leaf biomass, L VV σ^0 and branch biomass, and P band σ^0 and both branch and trunk biomass are illustrated in Figure 3. The relationships established included data for low biomass pastures.

	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

Table 2. Relationship between C, L and P band σ^0 and component biomass, expressed as the correlation coefficient (r^2).

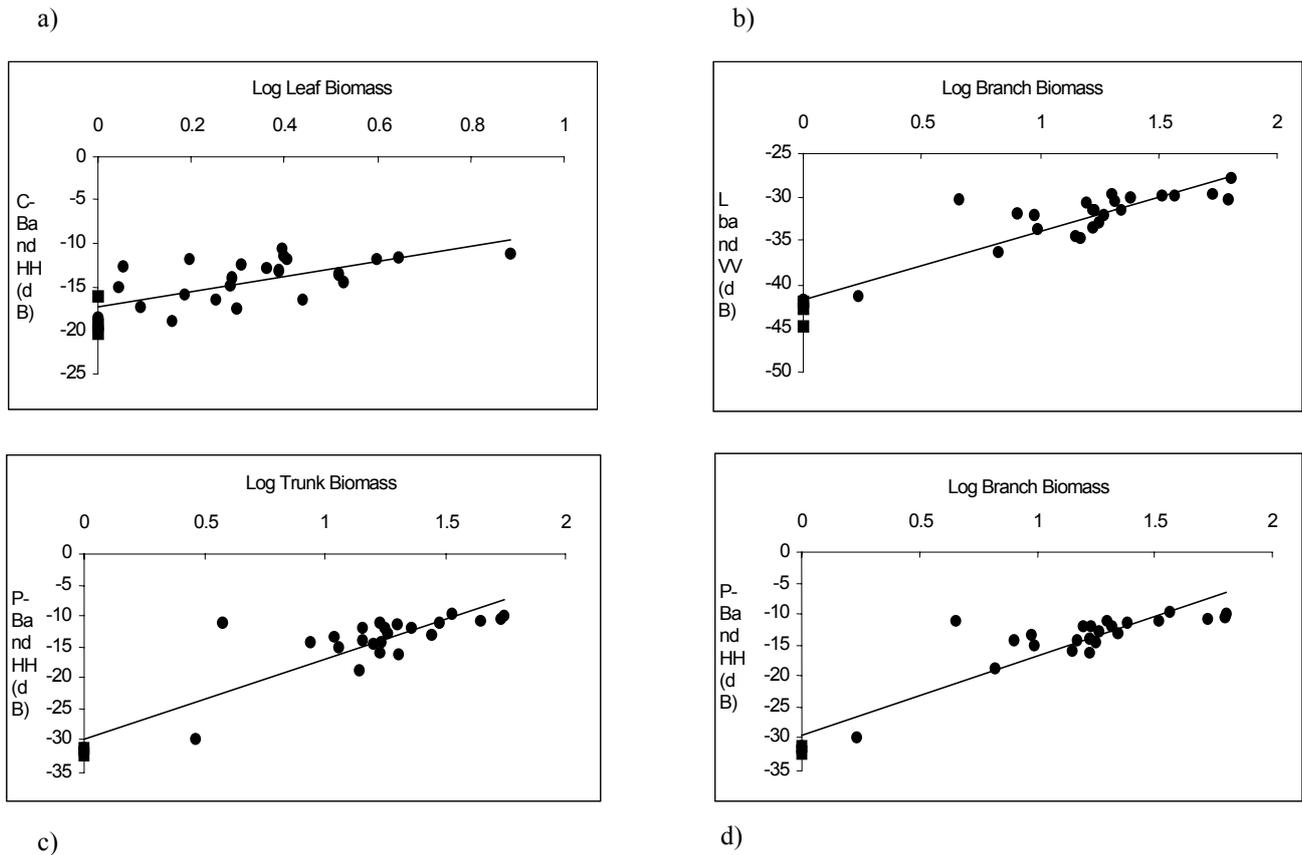


Figure. 3 Relationships between a) C band HH and leaf biomass, b) L band VV and branch biomass, c) P band HH and trunk biomass and d) P band HH and branch biomass, Talwood study region. (Pasture sites ■ woodland plots ●)

The strongest relationship with leaf biomass was obtained using C HH data, with backscatter ranging from -12 to -20 dB. The relationship was similar, although slightly weaker, with L VV data (range -15 to -23 dB) and was least with P band data (all polarisations).

The relationship with branch biomass was relatively weak using C HH 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 HH 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^0 (dB) at all wavebands and polarisations was observed, although the strongest relationship ($r^2 = 0.91$) was observed using P HV and 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 $20\text{-}30\text{ Mg ha}^{-1}$, 60 Mg ha^{-1} and $80\text{-}100\text{ Mg ha}^{-1}$.

8. AREAL ESTIMATES OF BIOMASS

The classification of SAR data is often based on the information contained within individual pixels. Such classifications are unlikely to provide satisfactory results due to the large amount of image speckle that results from coherent processing. A more reliable classification can generally be obtained using statistics of clusters rather than individual pixels. Simple averaging with an $n \times n$ pixel window centered on pixels of known interests is an example of this approach.

The image segmentation algorithm developed by Dong *et al.* (1997) uses a Gaussian Markov Random Field (GMRF) model to separate the SAR image into disjointed regions (or segments) that correspond to objects, or parts of objects,

which differ from their surroundings. The GMRF model is based on a normal or Gaussian distribution of the probability density function (pdf). SAR data are generally processed using multi-look averaging techniques to reduce the level of speckle and it has been shown that the pdf corresponds more to a K, or Gamma, distribution. However, according to the Central Limit Theorem in statistics, such distributions can be approximated to a Gaussian distribution with acceptable limits of error thereby allowing the application of the GMRF model. An advantage of the assumption of a Gaussian distribution is that mathematical descriptions for such distributions are more complete and the difference between segmentation results based on the Gaussian and Gamma distribution is small. Objects are segmented on the basis of the regional distribution of data values and their spatial relationships are described using first and second order statistics.

The GMRF model considers two regions to be separate if one or more of the following conditions is true:

- The first order statistics (i.e., the means for a single frequency image or the mean vectors for a multi-frequency image) differ.
- The second order statistics (ie., the variances for a single frequency images or the covariance matrices for a multi-frequency image) differ.
- The spatial textures differ.

Recent studies have shown that regions whose mean differences are as small as 0.5 dB (10%), and the ratios of the standard deviation to the mean are as high as 0.35, can be separated to an accuracy exceeding 95%. Subsequent classification of the segmented image is then based on a user-defined categorisation of information distributed across all segments. The segmentation procedure can be applied to single frequency, single polarisation or multi-frequency, multi-polarisation SAR images. Examples and maps derived from these techniques are presented in Dong, *et al*, 1999.

9. OTHER DATA

Under the Global Rainforest Mapping experiment (GRFM) being conducted as part of the JERS-1 Verification Program, large scale mosaics of Amazonia, Central Africa and South-East Asia using L-band imagery have been prepared under the auspices of the National Space Development Agency of Japan. A preliminary version of the North Australian portion of the South-East Asia mosaic has recently become available. The mosaic is made up of 50 satellite passes collected over Australia during 1996/97. Resampling and compression of the image data has resulted in 100 metre pixels with matching positional accuracy. Analysis of the radiometric variation between neighbouring swaths and thematic interpretation of the data have yet to be concluded. Very preliminary investigation of this data shows discernible patterns within the distribution of forests and woodlands of Northern Australia suggesting a potential for identifying regional land cover changes and for assessing environmental gradients within the vegetation biomes of Northern Australia.

10. 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 to the trunk biomass, but provided limited information on branch and leaf biomass.
- A strong relationship between L HH and above ground biomass was obtained when low biomass pasture sites were included.
- 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.
- 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.
- Saturation of C, L and P band data occurred at approximately 20-30 Mg ha⁻¹, 60 Mg ha⁻¹ and 80-100 Mg ha⁻¹.

The biomass of woodlands in Australia may exceed 150 Mg ha⁻¹ 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.

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 satellite borne ENVISAT ASAR, LightSAR and JERS-2 SAR are scheduled for launch and will be acquiring polarimetric data at C and L band. The ARC study will therefore provide some insight into the most suitable sensors for spatially estimating biomass on a regional basis.

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12. REFERENCES

- Australian Greenhouse Office, Canberra, Australia. <http://www.greenhouse.gov.au>, (1999).
- Beers, T., and Miller, C. (1965). Point Sampling: Research results, Theory and Applications. Purdue University, Agricultural Experiment Station Lafayette, IN. Research Bulletin. Aug. 1965, No. 786
- Bergen, K.M., Dobson, M.C., Pierce, L.E. and Ulaby, F.W., (1998). Characterising carbon in a northern forest by using SIR-C/X-SAR imagery. *Remote Sensing of Environment*. 63, pp. 24-39.
- Beaudoin, A., Le Toan, T., Goze, S., Nezry, E., Lopes, A., Mougin, E., Hsu, C.C., Han, H.C., Kong, J.A. and Shin, R.T. (1994). Retrieval of forest biomass from SAR data. *International Journal of Remote Sensing*. 15, pp. 2777-2796.
- Bureau of Resource Sciences (1999). http://www.brs.gov.au/land&water/landcov/alcc_results.html
- 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. *Proceedings, 9th Australasian Remote Sensing and Photogrammetry Conference*, pp. 1561-1580.
- Dilworth, J.R. and Bell, J.F. (1971). Variable probability sampling – variable plot and three P. (Corvalis: OSU Book Stores).
- Dobson, M.C., Pierce, L.E., and Ulaby, F.T. (1995). Knowledge-based land cover classification using ERS-1/JERS-1 SAR composites. *IEEE Trans. Geoscience and Remote Sensing*.
- Dong, Y., Forster, B.C., Milne, A.K. and Morgan G.A. (1998). Speckle suppression using recursive wavelet transforms, *International Journal of Remote Sensing*, pp. 19, 2, 317-330.
- Dong, Y., Forster, B.C., and Milne, A.K. (1999). Segmentation of radar imagery using the Gaussian Markov random field model, *International Journal of Remote Sensing*, pp. 20, 8, 1617-1639.
- Fransson, J.E.S. and Israelsson, H. (1999). Estimation of stem volume in boreal forests using ERS-1 C- and JERS-1 L-band SAR data. *International Journal of Remote Sensing*. 20, pp. 123-137.

- Foody, G.M., Green, R., Lucas, R.M., Curran, P.J. and Honzak, M. (1997). Observations on the relationship between SIR-C radar backscatter and the total biomass of regenerating tropical forests. *International Journal of Remote Sensing*, 18, 6 pp. 87-694.
- Green, R.M. (1998). Relationships between polarimetric SAR backscatter and forest canopy and sub-canopy biophysical properties. *International Journal of Remote Sensing*. 19, pp. 2395-2412.
- Harrell, P.A., Kasischke, E.S., Bourgeau-Chavez, L.L., Haney, E.M., and Christensen, N.L. (1997). Evaluation of approaches to estimating above ground biomass in southern pine forests using SIR-C data. *Remote Sensing of Environment*. 59, pp. 223-233.
- 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, pp. 135-143.
- Imhoff M. L., Sisk T. D., Milne A., Morgan G., Orr T. (1997). Remotely Sensed Indicators of Habitat Heterogeneity: Use of Synthetic Aperture Radar in Mapping Vegetation Structure and Bird Habitat *Remote Sensing of the Environment*. 60, pp. 217-227
- Kasischke, E.S., Christensen, N.L and Bourgeau-Chavez, L.L. (1995). Correlating radar backscatter with components of biomass in loblolly pine forests. *IEEE Transactions Geoscience and Remote Sensing*. 33, pp. 643-659.
- Kuhnell, C., Goulevitch, B., Danaher, T., and Harris, D. (1998). Mapping woody vegetation cover over the State of Queensland using Landsat TM. *Proceedings, 9th Australasian Remote Sensing and Photogrammetry Conference*. pp. 3201-3223.
- Luckman, A., Baker, J., Kuplick, T.M., Yanesse, C. and Frery, A.C. (1997). A study of the relationship between radar backscatter and regenerating tropical forest biomass for spaceborne SAR instruments. *Remote Sensing of Environment*. 60, pp. 1-13.
- Neldner, V.J. (1984). Vegetation survey of Queensland: South Central Queensland. *Queensland Botany Bulletin*, 3, Queensland Department of Primary Industries, Brisbane.
- Queensland Department Of Natural Resources. (1997). The Statewide Landcover and Trees Study (SLATS). Queensland Department of Natural Resources Interim Report, pp. 37.
- Ranson, K.J., Sun, G., Weishampel, J.F and Knox, R.G. (1997). Forest biomass from combined ecosystem and radar backscatter modelling. *Remote Sensing of Environment*. 59, pp. 118-133.
- Sader, S.A. (1987). Forest biomass, canopy structure, and species composition relationships with multipolarization L-band Synthetic Aperture Radar data. *Photogrammetric Engineering and Remote Sensing*. 53, pp. 193-202.
- 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, pp. 503-513.

13. BIBLIOGRAPHY

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