BNSC-LINK Programme

Project R4/039.

CARBON OFFSET VERIFICATION PROJECT

Final report (revised 23rd July 2003)

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1. Summary

The BNSC-LINK Carbon offset verification project has brought together a number of commercial partners (EcoSecurities Ltd, SGS (Société Générale de Surveillance) UK Ltd and Biffa Waste Services Ltd), with a number of academic partners (the Universities of Oxford and Swansea and the Centre for Ecology and Hydrology). The project was initiated out of a shared concern and interest in the challenge of forest carbon accounting in support of the Kyoto Protocol, and in particular the potential of remote sensing to constrain some of the uncertainty inherent in existing methods.

The project was built around two key aims:

(1) To investigate the capability of Synthetic Aperture Radar (SAR) remote sensing to estimate and monitor temporal change in biomass density of both managed and semi-natural forests, and

(2) To investigate the complementary use of optical and near infrared remote sensing for constraining and characterising forest ecosystem models for estimating NPP and carbon partitioning.

The project was also based on a general underlying rationale that as many methods of estimating carbon should be assessed as possible for two contrasting study sites. In practice this led to optical, radar and LiDAR remote sensing methodologies being compared with yield model based methods and ground measurements of carbon, in a comprehensive comparison of different methods.

The key landmarks of the project were that:

- A comprehensive assessment of the carbon partitioning of a semi-natural, deciduous woodland was conducted, creating one of the few studies of its kind.
- A comprehensive assessment of the ability to estimate stand age, height and volume from both AirSAR and E-SAR radar data was conducted.
- An investigation of the change in backscatter between the 1991 and 2000 data acquisitions and the accompanying change in stand volume and height.
- An examination of the possibility of estimating change in biophysical variables between two dates, based on change in radar backscatter using i) spaceborne data (1978 and 1997) and ii) airborne data (1991 and 2000).
- A novel methodology was developed enabling the derivation of canopy carbon content based on LiDAR derived canopy height in conjunction with yield tables (modified to characterize mixed age and mixed species semi-natural woodland).

2. Introduction and objectives

The Carbon offset verification project (subsequently referred to as the carbon project) was developed as a common concern of the carbon accounting industry (specifically SGS and EcoSecurities) and the academic community, echoing international scientific and political concern. The project was led by the Environmental Change Institute at the University of Oxford, and involved SGS and EcoSecurities as the commercially interested partners, alongside the University of Swansea and CEH Monks Wood, as the academic partners (Appendix 1). After a 12-month delay due to problems associated with (i) recruitment of the postdoctoral scientist, and (ii) obtaining an all-party signatory to the memorandum of partnership, the project formally began in October 2000. The primary phase of the project finished with the final project meeting and the final project report in December 2002. [Answer the comment from Geof Wadge: If the project was supposed to run from November 1999 to November 2002, why did it only start in October 2000, after the remote sensing campaign was held.] However, a secondary phase of the project, based primarily around the PhD studentship associated with this project, is expected to be completed around December 2003.

The specific work completed for this project to date included the following:

1. The comparison of a ground-based methodology of assessing woodland vegetation density and cover at different heights with the results provided by remotely sensed data. In addition to the historical ground survey data existing for both the Thetford and Monks Wood study areas, a new and comprehensive survey of vegetation structure for both sites was conducted during the E-SAR campaign.

2. The evaluation of the sensitivity of both airborne and satellite SAR to the change in biomass densities of various Thetford sites and tree species over time by comparing calibrated backscatter values derived from AirSAR and E-SAR data sets.

3. The development of a method of deriving carbon based on LiDAR-derived tree height and modified yield models for deciduous forests.

4. The evaluation and development of the interface between the existing models of yield and carbon partitioning and the remote sensing data.

In addition, as part of the D.Phil. research funded under this project, the following objectives are ongoing with an expected date of completion being December 2003 (the results of this work will be published as an annex to this report at that time):

5. To investigate the use of optical remote sensing data to both support stand classifications and estimate the fraction of photosynthetically active radiation absorbed by the forest canopy (fPAR) to constrain a light-use efficiency (LUE) model of net primary productivity for comparison with SAR estimates of biomass density (ongoing).

This report is based around two main sections:

- i) The scientific achievements, which highlights the project milestones.
- ii) The interpretation of the results, specifically the perspective of SGS, EcoSecurities and CEH Bush Estate on the relevancy of the results for their commercial undertakings. Plus, a consideration of the future opportunities for all the partners to develop or exploit this work.

3. Background and context

3.1 International issues

At the Earth Summit in Rio in 1992, under the United Nations Framework Convention on Climate Change (UNFCCC), the UK and other developed countries agreed a voluntary target of taking measures aimed at returning their emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) to 1990 levels by 2010. At Kyoto in December 1997 the 174 parties to the convention signed up to a Protocol for reducing developed country emissions of a basket of the six principal man-made GHGs overall to 5.2% below 1990 levels over the period 2008-2012. In contrast to 1992, this target would be a legally binding commitment. The Kyoto Protocol establishes three ‘flexible mechanisms’ that can contribute to achieving emissions reduction commitments:

(1) Joint Implementation (JI),
(2) the Clean Development Mechanism (CDM),
(3) International emissions trading.

These mechanisms allow countries to achieve part of their legally binding commitments by actions taken to reduce emissions abroad. Emissions trading enable countries achieving greater reductions than needed to meet their target to sell the surplus to other countries. Joint Implementation and the Clean Development Mechanism allow countries with targets to receive a credit for project-based activities that reduce emissions in other countries. Work is continuing at international level to finalise the detailed rules and procedures for the operation of these mechanisms.

Article 3.3 of the Protocol identifies that, along with the need to control emissions, there is a need to preserve and enhance the amount of carbon stored in the terrestrial biosphere, most of which is in forest ecosystems. Vegetation, through the process of photosynthesis, transform carbon dioxide into carbohydrates which are stored into plant tissues during growth. Through this process, growing vegetation provides a potential sink to this greenhouse gas, thereby potentially offsetting emissions (carbon offset).

To this aim, there are three separate reporting requirements in the Kyoto Protocol as it relates to forests:

(1) land use change such as reforestation, afforestation and deforestation
(2) carbon stocks since 1990
(3) forest inventory

Under the Protocol, nations are expected to modify their national forest inventories to include measurements to meet the specific reporting needs of the Protocol (EU, 1998). A variety of international carbon offset programmes have been initiated since. Over the same period, a series of GHG regulatory bodies have been created to control the development of these activities.

3.2 Carbon accounting companies

Since reliable third party verification of carbon offsets is required by many GHG regulatory bodies, SGS Ltd., the proposed end-user and the world’s largest international testing, inspection, and monitoring organisation, is offering a service of analysis and verification of carbon offset, or emission reduction, projects. This service was developed together with EcoSecurities Ltd., a firm specialising in policy and environmental technologies and finance, with offices in UK, USA and

Brazil. EcoSecurities Ltd, one of the project partners, was the developer of the world's first commercial verification service for forestry carbon offset projects, currently under long-term license to SGS Forestry.

The carbon offset verification service consists of a formal analysis of project concept and design, a risk and uncertainty analysis, monitoring of project implementation, and verification, and the quantification and certification of projected and achieved emission reductions. The service is available to both buyers and sellers of carbon offsets, and is also relevant to GHG regulatory bodies and other interested parties. SGS views the offering of this service as being a risk management tool for all parties in this emerging field.

Changes in biomass density, resulting from tree growth, stand thinning, mortality and logging, are not easily obtained because of the need for extensive and regular field surveys and allometry. The SGS methodology is currently based upon extensive and permanent sampling plots, field measurements and Forestry Commission and other published yield tables. However, the need for a regular surveillance program for verification of project development and certification of achieved offsets or emission reductions, requires periodic verification of carbon achievements through field inspections and allometric monitoring, which is very labour-intensive and time consuming.

3.3 Remote sensing of forest resources

In recent years, the potential of Airborne Laser Scanning (ALS) and Synthetic Aperture Radar (SAR) has been widely investigated for monitoring forests' resources at regional and national scales and for developing forest inventory systems.

ALS operates on a principle called Light Detection And Ranging (LiDAR). A recent development, this approach allows direct measurement of 3-dimensional forest structure including canopy height. Using a pulse generated between the visible and the near infrared radiation portion of the electromagnetic spectrum (~1064 nm), a lidar system monitors the travel time between the sensor and the target on the ground. This elapsed time is measured using ultra-accurate clocks and provides elevation information of targets on the ground. The accuracy of the timing is crucial, as it determines vertical accuracy. Some of the most advanced systems can now achieve 5cm vertical accuracy. The elevation information is derived from the first and last significant return of the laser pulse. When applied to forestry, the first return pulse can provide tree canopy height information and the last return pulse can provide ground surface elevation, from which estimates of tree canopy height can be derived (Lefsky *et al.* 2002). When combined with modelling approaches, this technology provides a potentially powerful tool for monitoring forest growth and for estimating carbon storage. Although promising, the use of Lidar for vegetation mapping remains however at an early exploratory stage. Additionally, the absence of satellite based Lidar sensor limits its use for monitoring at regional and national scales.

SAR systems generate pulses in the microwave region of the spectrum, which is of sufficiently long wavelengths not to be significantly affected by atmospheric attenuation. This results in an operating capability independent of cloud cover. Importantly, microwave interactions are sensitive to the roughness and physical geometry of forests, an asset which, when combined with the ability of the radiation to penetrate forest canopies, results in the sensitivity of SAR backscatter to key biophysical variables, such as tree density and above ground biomass density (Beaudoin *et al.,*, 1994; Baker *et al.,*, 1994; Green *et al.,*, 1996, Green 1998a & 1998b).

The sensitivity of radar backscatter to above-ground biomass density is both wavelength and polarization dependent. This relates to the depth of penetration of different wavelengths, typically concentrating on the dominance of volume (canopy) scattering in X-band (3 cm) and C-band (5 cm) in contrast to branch scattering at 23 cm (L-band) and trunk-ground interactions at P-band (50 cm) (Ranson and Sun, 1994). Whereas short wavelength X- and C-band backscatter is sensitive mainly to canopy architecture (e.g. Green, 1998a), it is the longer wavelength L- and P-band backscatter that is highly correlated with forest above-ground biomass density. As Baker et al., (1994) also demonstrated, the cross-polarized term is often most strongly correlated with forest biomass density. Relationships between backscatter and biomass density are characterized by a saturation of the radar signal before reaching high bole volume (Imhoff, 1995). Dobson et al., (1992) analysed radar responses at L-, P- and C-band to forest biomass density and found an approximately linear response of backscatter with increasing biomass density with wavelength dependent saturation levels around 200 t ha-1 for P-band and 100 t ha-1 for L-band. In the study of Imhoff (1995) saturation was reached at 100 t ha-1 for P-, 40 t ha-1 for L- and 20 t ha-1 for C-band in coniferous and broadleaf evergreen forests. Luckman et al., (1998) found a saturation at 60 t ha-1 for L-band in tropical forests. The accuracy with which biophysical parameters can be retrieved from SAR measurements of forests depends considerably upon vegetation structure and ground conditions (Baker and Luckman 1999). Accordingly, the opportunity to evaluate SAR remote sensing over previously monitored study areas of known characteristics, whereby new techniques and sensors can be tested and which can draw upon the previous analysis, is complementary. The use of airborne SAR data provides us with a comparative approach

4. SCIENTIFIC ACHIEVEMENTS

The key scientific achievements of the project were:

1) Carbon map produced for a deciduous UK woodland, including a comprehensive assessment of carbon partitioning. Leading to the important result that current estimates of deciduous woodland carbon content could be underestimated by approximately a third, in part, due to the exclusion of understorey carbon content.
2) Selection and validation of a yield model suitable for deciduous species in a semi-natural woodland.
3) Maps of LiDAR derived carbon for Thetford (coniferous site) and Monks Wood (deciduous site).
4) Derivation of a method of converting tree height estimates to carbon estimates. The methodology was developed for deciduous semi-natural woodland and subsequently modified for coniferous plantation forest.
5) High accuracy carbon, volume, height and age estimates from multi-channel airborne radar data, with RMSE of typically about 10%.
6) Estimation of rate of stand height and volume change from airborne and spaceborne radar data, with high accuracy (RMSE of 0.23m for pre-saturation stands).
7) Comparison of four different contrasting methods of estimating stand height and stand carbon. The methods in question were based on LiDAR data, radar data, FC yield models and field measurements respectively.

4.1 Carbon account of a deciduous woodland (Monks Wood)

Two sets of fieldwork were conducted under the Carbon project, during summer 2000. The purpose of the field campaigns was to collect data to validate the processing and analysis of the SHAC E-SAR and HyMAP data. The Carbon project was centred on field sites at Monks Wood, Cambridgeshire and Thetford Forest, Norfolk (Figure 1). Thetford Forest is a primarily coniferous Forestry Commission (FC) site and subject to standard FC management practices. The FC maintain a GIS containing information about each of the Thetford stands, including species, age and yield class information. Monks Wood is a small area of semi-natural mixed deciduous woodland, which is structurally more heterogeneous than the Thetford site. Because of its status as a national nature reserve, the minimal intervention policy at the Monks Wood site means that less information exists for the stands, although generally the dominant species is known.

It is important to note that the key purposes of the fieldwork were different in both sites. At Thetford the primary aim was to allow a check on the accuracy of the FC GIS database for Thetford. At Monks Wood no such database existed. In addition, the highly heterogeneous mixed deciduous nature of the wood combined with the lack of existing knowledge about the carbon dynamics and stores of non-plantation forest in general, and deciduous woodland in particular, meant that a much more intensive methodology for determining stand characteristics was required. Due to time constraints, this research effort resulted in a less spatially extensive fieldwork campaign.

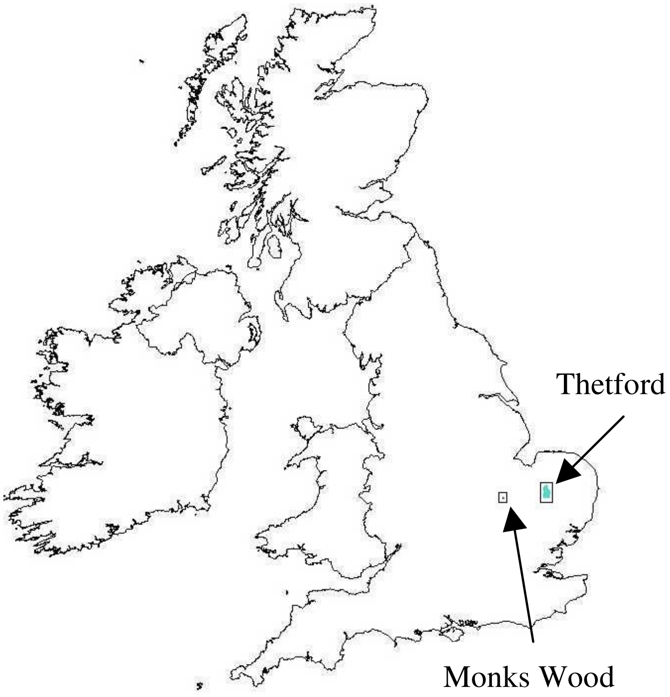

Figure 1: Location of the Monks Wood and Thetford sites, within the UK.

The Monks Wood fieldwork provided a comprehensive, generally non-destructive ground-based quantification of carbon in all significant above and below-ground forest components for five stands Like most patches of natural woodland in the UK Monks Wood does not have easily identifiable areas of a singles species, so it was difficult to identify homogeneous woodland ‘stands’. However, five contrasting stands were identified which contained relatively homogenous species composition and environmental characteristics. Full details of the study are given in Patenaude *et al.,* 2003.

The total carbon content of the five stands varied from 346 to 616 tonnes per hectare (t ha^{-1}), with the mean carbon content of the forest components comprising approximately:

- 2 t ha^{-1} for deadwood.
- 3 t ha^{-1} each for foliage
- 3 t ha^{-1} ground vegetation/litter.
- 18 t ha^{-1} for understorey shrubs and small trees.
- 28 t ha^{-1} for all roots.
- 78 t ha^{-1} for overstorey trees.
- 335 t ha^{-1} for soils.

The field campaign was essential for validating the results obtained from the remote sensing analysis. The results suggest that if the stands sampled at Monks Wood are representative of broadleaved woodlands in Great Britain then the inclusion of understorey vegetation in these estimates would result in an estimate of 92.6 Mt carbon in total in the broadleaved woodlands of the UK. This contrasts with a previous estimate of 61.9 Mt carbon, which excluded the carbon content of understorey vegetation. The results highlight the importance of broadleaved woodlands as carbon stores and in particular the importance of the role of understorey vegetation. This will impact on current and future initiatives for developing British woodlands to offset greenhouse gas emissions. The importance of understorey vegetation is also problematic for remote sensing technology, which observes the top of the canopy, and in general, tends to be insensitive to understorey vegetation. Section 4.4 describes a method, which includes understorey carbon in a LiDAR based carbon estimation method.

4.2 Tree height to carbon conversion: deciduous woodland

Calculating wood or forest carbon content from tree height involves 2 key calculations (Figure 2). The conversion to stemwood volume is conducted with specially developed yield tables (see section 4.3) and requires mean tree height to be converted to top height. Top height is a standard forestry measure and is defined as the height of the 100 trees with the largest DBH per hectare (Edwards & Christie, 1981).

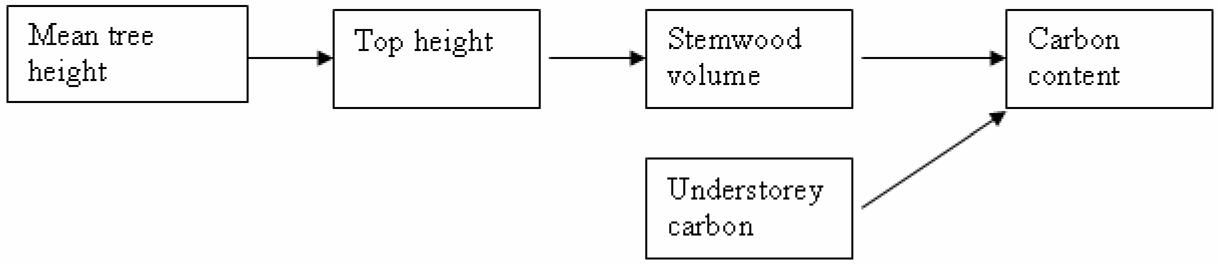

Figure 2: Keys stages in calculating carbon content for deciduous woodland from tree height.

The average height was converted to top height for each pixel (as the method is designed for use with remote sensing data) using a relationship between top height and average height derived from (Hamilton, 1975). No data relating average height to top height for deciduous species were available so 10 coniferous species were selected and their relationships averaged. The top height per pixel was then used to derive stemwood volume per pixel from the yield model. The yield model was selected by comparing the DBH-age relationship between field collected tree cores and the empirical yield models (Edwards and Christie, 1981). Stemwood volume was converted to carbon content using a simple model based on empirically determined coefficients (equation 1). For further details see Patenaude *et al*., 2002.

$$C_{content} = V_{stem} * BE * DM * CC \qquad [1]$$

Where:

Stemwood volume (V_{stem}).	In m^3 ha^{-1}. Derived from the yield models.
Biomass expansion factor (*BE*).	Converts stemwood volume to total above ground volume. BE is assumed to be 1.36 for UK deciduous forests.
Dry mass conversion factor (*DM*).	Converts total volume to dry mass. *DM* is assumed to be 0.55 for UK deciduous forests.
Carbon content conversion factor *(CC).*	Converts dry mass to carbon content. *CC* is assumed to be 0.49 for UK deciduous forests.

Conversion and biomass expansion factors above were based on Dewar and Cannell (1992), Milne *et al.* (1998) and Salway *et al.* (2001).

Monks Wood, like most deciduous woodlands, has a significant understorey, which also presents an important carbon store. For stands composed of large and tall trees, the carbon content from the understorey may be undetectable i.e. unseen by the sensor as it remains overshadowed by the dominant canopy. Thus, for stands of trees above a selected height threshold, the carbon content in the understory pool was derived as a function of overstorey carbon content. This function was derived from the field work data for the 48 plots surveyed.

4.3 A yield model suitable for deciduous species in a semi-natural woodland

Yield models are species-specific empirical models developed from extensive ground-based forest mensuration. The collected data, summarised into empirical yield tables, are used for the derivation of relationships between forest variables such as diameter at breast height (DBH), basal area, age, top height and stemwood volumes. Yield classes are defined, which implicitly account for the influence of environmental conditions and predict maximum growth in m^3 ha^{-1} yr^{-1} (Edwards and Christie, 1981). When yield classes (YC) are assessed accurately, forestry databases and yield models allow for relatively accurate prediction of growth. These models have been developed for single-species and even-aged plantations. Since limited information is available on growth variables in natural forests, standard yield models are used here to estimate stemwood volume as a function of top height.

Part of the novel aspect of the work was the development of a method to assess the utility of existing yield models and to select the most appropriate. Based on an analysis of the main species at Monks Wood the sycamore-ash-birch (SAB) yield model was identified as having potential. The age-DBH relationships obtained from tree cores for the dominant species where then compared to those from the SAB models for various yield classes (Figure 3). The results support the selection of SAB YC 4 for the overstorey trees in Monks Wood. The relationship between top height and stemwood volume was then derived from the yield tables of SAB YC 4 and Oak YC 4 (Patenaude *et al*., 2002).

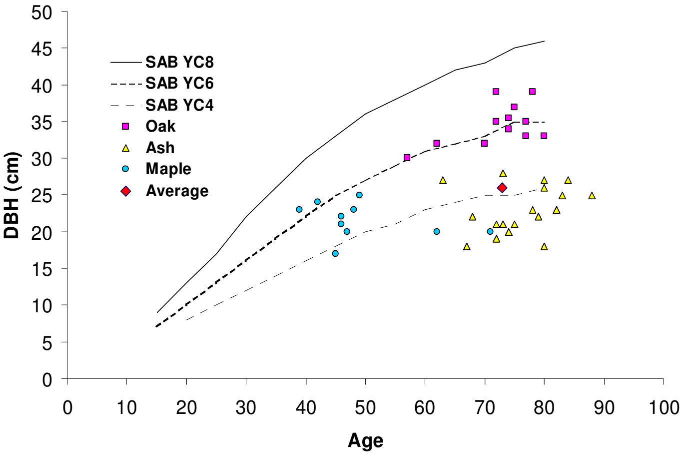

Figure 3: DBH-age comparison between field collected tree cores and the SAB empirical yield models YC 4, 6 and 8. The average shows the correspondence of the field data with the SAB model YC 4. Models were derived from Edwards and Christie (1981).

4.4 LiDAR derived carbon: Monks Wood

In addition to the SHAC E-SAR and HyMAP data, LiDAR derived canopy height data (courtesy of Ross Hill, CEH Monks Wood) became available for the Monks Wood site. The availability of this data was not envisaged at the start of the project and so does not appear in the project proposal. However, LiDAR is currently believed to be of the most promising remote sensing approach for quantifying biomass in forest. Hence, making use of the availability of this dataset has allowed for the investigation of Lidar to evaluate the spatial variability of biomass and carbon over the Monks Wood site. Due to the limited number of ground sites that could be surveyed at Monks Wood the spatial variability was a considerable uncertainty. Using an approach that combined Lidar data with the yield models, our aim was to develop a simple method for verifying carbon stocks in temperate deciduous forests such as Monks Wood.

Image data were acquired using an Airborne Laser Terrain Mapper (Optech ALTM 1210) on the 10th of June 2000. From this data a map of canopy height was derived (Hill *et al.,* 2002). Validation of this canopy height with ground based data showed that the lidar dataset systematically underestimated real height by as much as 2.09 meters for shrubs and 3.06 meters for trees (see Hill et al. 2002). This is due to the penetration of the lidar pulse beyond the top of the canopy before returning a significant signal. After calibration of the data to correct for this systematic underestimation, the canopy height estimates were converted to carbon estimates using the method outlined in section 4.2. Comparing the average carbon contents per stand reveals that both methods (field work versus LiDAR derived carbon) are in strong agreement ($R^2 = 0.9254$, $P<0.05$) (Figure 4). The linear regression line suggests that the ALS method appears to overestimate slightly compared to the ground derived carbon content of the stands. However, all ALS values except stand 2 fall within the confidence limits of the ground data (see figure 4). The variability within each stand is very large which could explain the discrepancy observed in stand 2 between the ground and the ALS carbon contents. In fact, even very slight disparities between the location of the plots on the image and on the ground could induce large variation in the results.

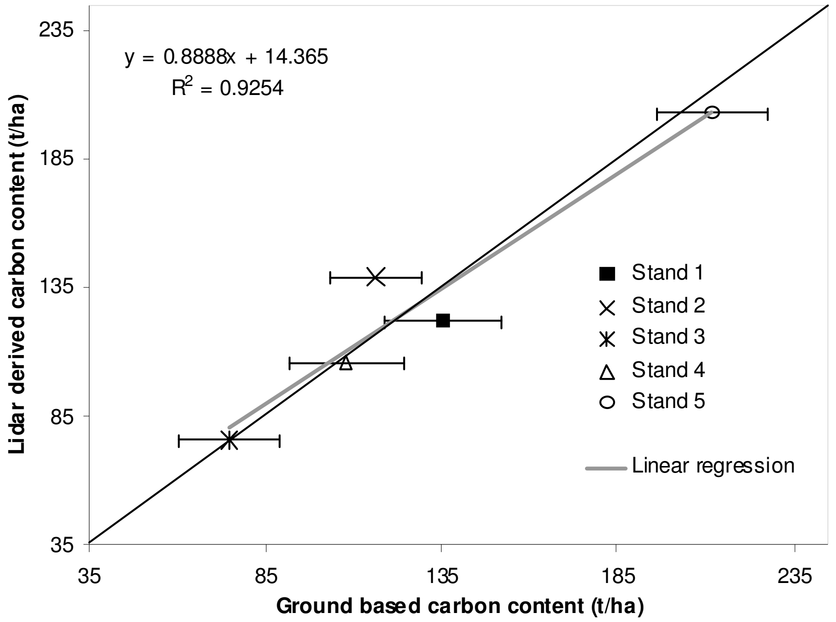

Figure 4: Carbon content estimates from ground survey and ALS based model for the 5 stands (R^2=0.9254,P<0.05). Confidence limits at the 95% level are given for the total carbon content derived from the ground data.

This work demonstrated that a combination of yield tables and a canopy height map derived from ALS has a lot of potential for deriving carbon content per hectare for semi-natural woodland. Additional work is required to identify the various sources of errors and their propagation through the process. In particular, the problems encountered in this work with the lack of existing data on growth patterns, yield models etc. for natural, unmanaged forest ecosystems in the UK highlights a serious lack of knowledge about the role of natural deciduous woodland in the carbon cycle. The use of yield models may be appropriate for plantations but multi-species, multi-aged ecosystems involve other ecological parameters such as intraspecific competition, which are not taken into account. Little information is available on the growth and mortality patterns and modelling of understorey vegetation, which can represent an important component of the carbon stores in unmanaged woodland. It is also not clear how transferable the method is, in particular because of the site-specific nature of the empirical compensation for the carbon in the understorey, which relies on relationships derived for the Monks Wood site. Further work is required to develop an understanding of, and empirical relationships for, the relationship between canopy overstorey and understorey carbon content for various types of deciduous woodland.

4.5 Estimates of stand volume, height and age from airborne radar data

Two main radar remote sensing data sets were used under this project. The E-SAR sensor was flown over the Thetford site on 31st May 2000, with data collected at a number of bands and polarisations (L-HH, L-HV, L-VV, X-VV, plus repeat-pass L-band fully polarimetric data). The AirSAR sensor was flown over the site on 28th July 1991, with data collected in a range of bands and polarisations (P-HH, P-HV, P-VV, L-HH, L-HV, L-VV, C-HH, C-HV, C-VV). The AirSAR data covered an area of 12km by 12km at a 10m spatial resolution, whereas the E-SAR data covered a 5km x 8km area at a higher resolution of 1m. The inclusion of P-band data in the AirSAR data set is significant as P-band data is more sensitive to changes in biomass than L-band data (Dobson *et al.* 1992; Imhoff 1995), so the *a priori* expectation was that the AirSAR data set will produce better estimates of biomass and related variables than the more recent E-SAR data set. However, the E-

SAR Interferometric SAR (InSAR) capability using repeat-pass imagery was exploited by using the interferometric coherence (the complex interferometric correlation coefficient) for each L-band polarisation as a data source, as Luckman *et al.* (2000) showed it to be sensitive to biomass.

To derive relationships between the radar data sets (AirSAR or E-SAR) and a given variable a cross-validation method was used. The data were randomly divided in half. Half the data were used as a training data set to train the neural network and derive the empirical relationships, whilst the other half was used as a testing data set, to assess the ability of the proposed relationships against unseen data. All R^2 and RMSE values quoted, unless otherwise stated, are for the relationships when applied to the unseen test data set and not the data set that the training process was applied to. Separate relationships were derived for both Scots Pine and Corsican Pine stands. Full details of the neural network methodology can be found in Rowland *et al.*, 2002.

Table 1 details the most accurate estimates of age, height and volume for both the E-SAR and AirSAR sensors using neural network and statistical models. This enables a comparison of the AirSAR and E-SAR sensors, along with a comparison of the neural network solutions and the statistical model solutions. The key results were:

- In all cases the AirSAR estimates are of higher accuracy than the E-SAR sensor estimates. The difference between the accuracy of the neural network estimates for both sensors differs by less than 5%. This is small given the differences between the sensor characteristics, in particular, the inclusion of the P-band might be expected to give the AirSAR data a substantial advantage over the E-SAR data
- The difference between AirSAR and E-SAR is most pronounced in the statistical relationships, where the E-SAR RMSE values are up to 50% higher than the corresponding AirSAR values (i.e. AirSAR RMSE of 8.91 years cf. E-SAR RMSE of 12.13 years). For both AirSAR and E-SAR the neural network results produce higher accuracy than the statistical relationships.
- Figure 7 shows the effects of saturation point above 15m. Saturation point is the point at which changes in forest structure (age/height/volume) no longer produce a change in radar backscatter. The lack of sensitivity to changes in structure lead to higher errors in the estimates of height for stands taller than 15m.

The best estimates of stand timber volume, age and height were produced using neural networks and AirSAR data, which include P-band observations. . However, the inclusion of the E-SAR coherence data seems to compensate for the lack of P-band data, so the resulting E-SAR neural network estimates are only marginally less accurate than the AirSAR estimates.

Table 1: Summary of best AirSAR and E-SAR results from neural network and statistical models for Corsican Pine at Thetford, UK. ([a] n1 is number of stands in training data set, n2 is number of stand in testing data set.)

Sensor	Method	Age RMSE (R^2)	Height RMSE (R^2)	Volume RMSE (R^2)
E-SAR (n1=140; n2= 141)[a]	Neural network	**6.61yrs (0.88)**	**2.51m (0.90)**	**64.54 m^3/ha (0.84)**
	Statistical model	**12.13yrs (0.61)**	**4.15m (0.73)**	**121.41m^3/ha (0.48)**
AirSAR (n1=137; n2=138)[a]	Neural network	**6.33yrs (0.88)**	**2.48m (0.90)**	**54.03m^3/ha (0.87)**
	Statistical model	**8.91yrs (0.77)**	**3.53m (0.81)**	**76.77m3/ha (0.75)**

The results can be visualized in a number of ways, either as scattergraphs of estimated versus actual values for the variable in question (Figure 5), or alternatively as maps (Figures 6). In Figure 2 the RMSE for the network used to generate the radar derived height map is 2.54m for the test data set and 2.26m when all the stands are used. The higher accuracy produced when all the stands are used is a sign of the tendency of the network to overtrain. The spatial distribution of the error in stand height is shown in Figure 6. Note similar scattergraphs and maps are available for tree volume, stand height and stand age for 2000 and 1991 on the BNSC-LINK Carbon offset verification project CD-ROM.

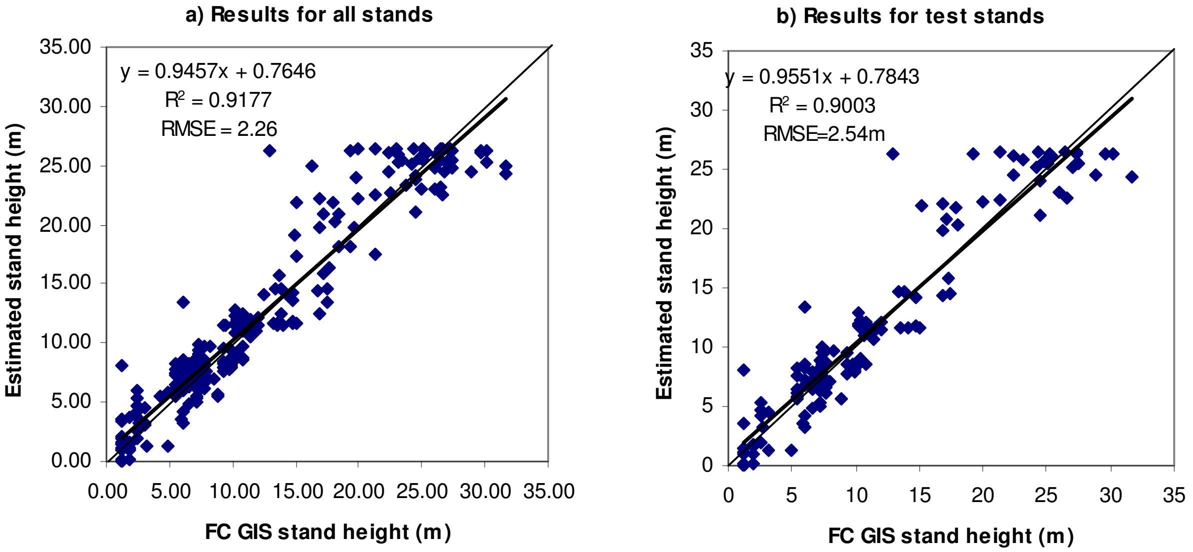

Figure 5: Plot of estimated tree height against actual tree height using E-SAR data to estimate height for a) all stands in image and b) test stands only.

4.6 Estimating stand change over time

For carbon offset verification studies it is important to be able to monitor change and growth of forest ecosystems over time. The estimation of change in a variable such as height or volume over time presupposes that the change in the variable over the time period in question produces greater variability than the inevitable error in the estimates of the variable in question. Assessing this condition with respect to the AirSAR 1991 and E-SAR 2000 data shows:

1. the range of *change* in tree height was from 1.53m to 5.74m derived using the FC GIS database and yield models;
2. the best estimates of absolute tree height have a RMSE of approximately 2.5m in both the AirSAR and E-SAR cases.

Consequently, the expectation is that the error in tree height estimation is likely to dominate the estimates resulting in poor estimates of tree height change.

Two basic methods can be defined for quantifying change in biophysical variables with remote sensing over time. First the direct method which estimates change from the difference in backscatter between the two years and second the indirect method where height change is calculated from estimated height in the later year minus the earlier year (Balzter *et al*,. 2003).

4.6.1 Direct method

The aim was to assess the ability to estimate forest change over a 9 year period, using L-band, the only band common to the AirSAR and E-SAR data acquisitions for Thetford, so the difference in L-band backscatter data were used to train a number of neural networks to estimate both absolute and percentage change in stand height and stand volume (Rowland *et al.,* 2003a). The results in Table 2 and Figure 7 show the RMSE for estimation of tree height change at 0.45m is much lower than expected. The change in height of stands below saturation point (RMSE =0.75m, R^2=0.32) is more accurately estimated than for stands above saturation point (RMSE=0.23m, R^2=0.78). Table 2 shows that in general the change between 1991 and 2000 is well estimated from the radar data. The percentage RMSE (PRMSE) is included to allow comparison of the accuracy of the different variables. All the PRMSE are 10% or below with the exception of volume change at 15.98%. The high similarity is assumed to be a result of the high correlation between the variables being estimated. These results are important for carbon offset verification, as they suggest that (especially for younger stands), radar multi-temporal remote sensing can have a role to play in monitoring stand growth rates.

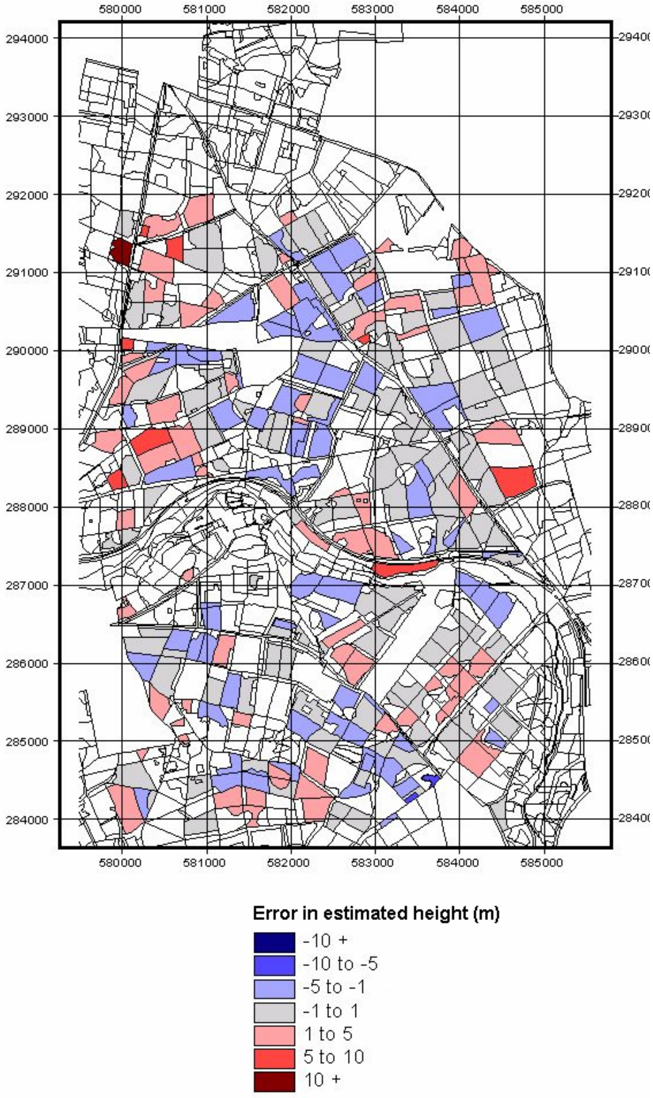

Figure 6: Difference between FC GIS stand height and estimated stand height. NB positive values show overestimation by the neural network and negative values show underestimation.

Table 2: Summary of the best estimates of change 1991 - 2000.

	RMSE	PRMSE(%)	R^2
Percentage height change (%)	46.27	9.00	0.88
Percentage volume change (%)	7.77	8.86	0.94
Height change (m)	0.45	10.27	0.87
Volume change (m^3 ha^{-1})	16.91	15.98	0.46

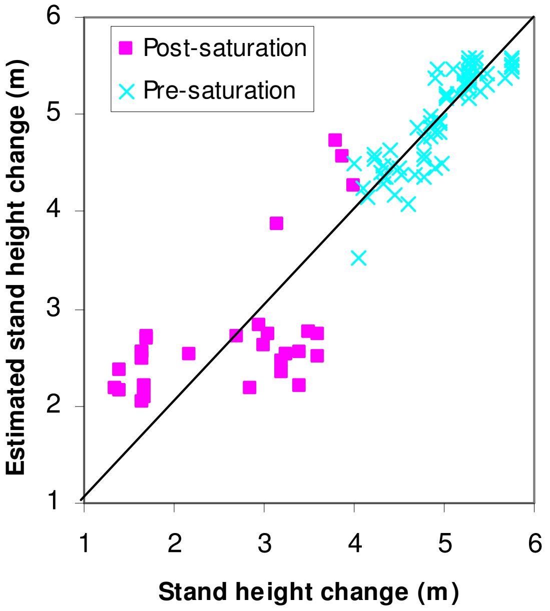

Figure 7: Estimated height change between 1991 and 2000 using change in L-band backscatter.

4.6.2 Indirect method

The indirect method involves identifying the most accurate set of estimates of tree height for both the AirSAR and E-SAR data sets and then calculating the difference between the two sets of estimates (Figure 8, Table 1). Figure 9 shows the actual change derived from the FC GIS plotted against the change between the AirSAR and E-SAR estimates. The estimated change values are very poor, as the error from both sets of sensor data is propagated through into the final estimate of tree height change. The final RMSE of 3.18m is, as Figure 9 illustrates, too high for the estimation of the narrow range of tree height change in this example. The key message though is that the accuracy of absolute estimation of tree height at around 2.5m is not high enough to accurately estimate change over a 9 year period using this method. Until the accuracy improves significantly it is unlikely that this method of quantifying change will have any practical application.

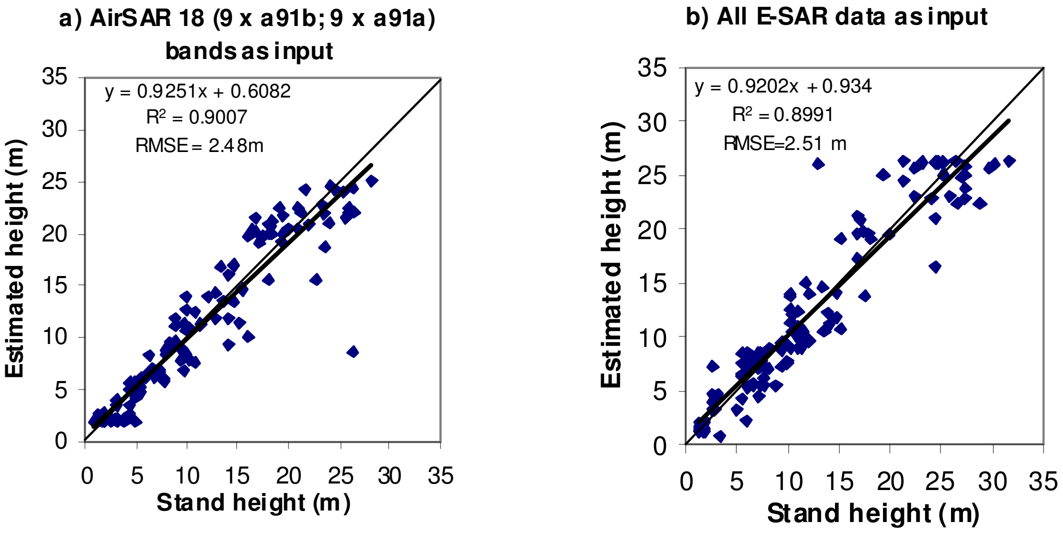

Figure 8: Best estimates of tree height for a) AirSAR data and b) E-SAR data.

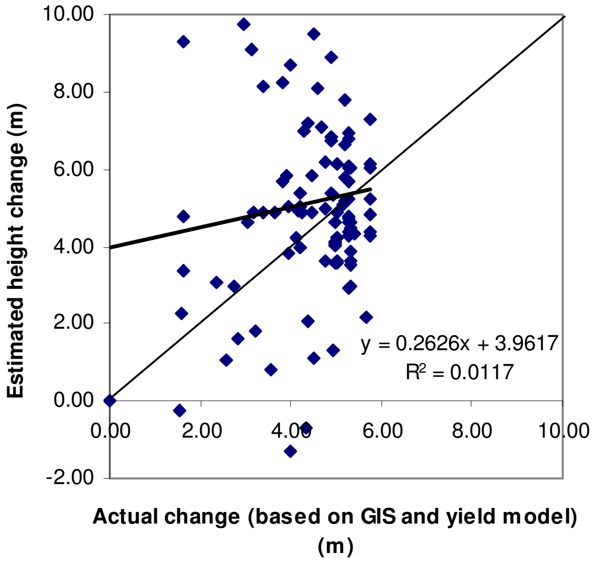

Figure 9: Comparison between actual height change and estimated height change.

A similar experiment was also conducted over a longer time period to investigate the capability of spaceborne radar to detect backscatter change and relate it to tree growth (Balzter *et al.,* 2003). A SEASAT SAR image from 1978 and a JERS-1 SAR image from 1997 for Thetford were used to retrieve tree growth for the Corsian Pine stands. Full details of the experiment are described in Baltzer *et al.,* 2002 (included in February 2002 deliverables).

4.6.3 AirSAR and E-SAR difference image

Figure 10 shows stand height based on the FC GIS and yield models. Figure 11 shows the per-pixel difference in backscatter between the incidence angle corrected AirSAR and E-SAR data. Given the general relationship between backscatter and biomass/related variables we expect to identify three main types of behaviour:

- New growth - negative backscatter difference (i.e. AirSAR backscatter higher than E-SAR) due to the stand being clearcut and replanted between 1991 and 2000. Therefore the trees are between 0 and 9 years.
- Young growth - strong positive backscatter difference (i.e. E-SAR backscatter higher than AirSAR backscatter) due to the strong increase in biomass (stem and foliage) equivalent to the 10-30 year stage of tree growth before the stand reaches densities where it causes the radar signal to saturate.
- Mature trees – no change (or very low change) in backscatter as expected for trees that have reached the saturation point.

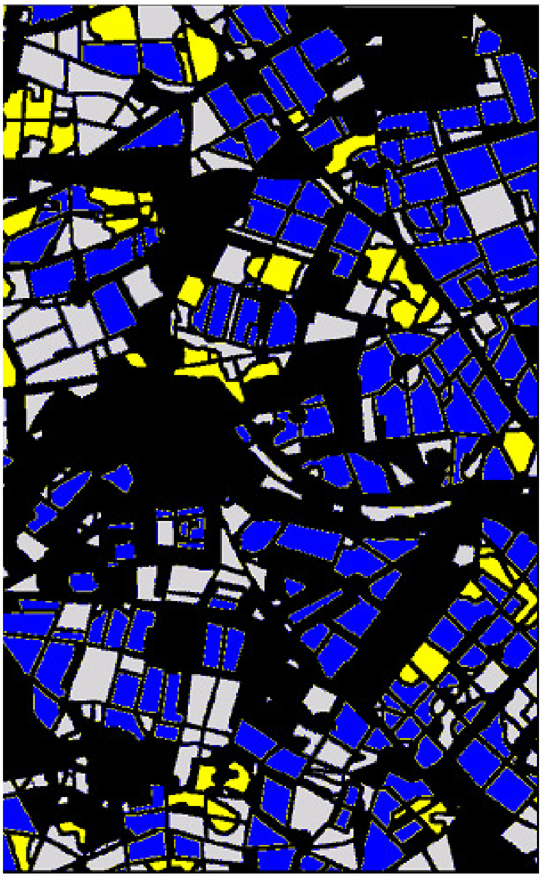

Figure 10: age map for Corsican and Scots pine stands for year 2000 (colour coding: Yellow – young trees (0 –9 yrs); Blue – growing stands (10 – 30 yrs); Grey – mature stands (30+ years)).

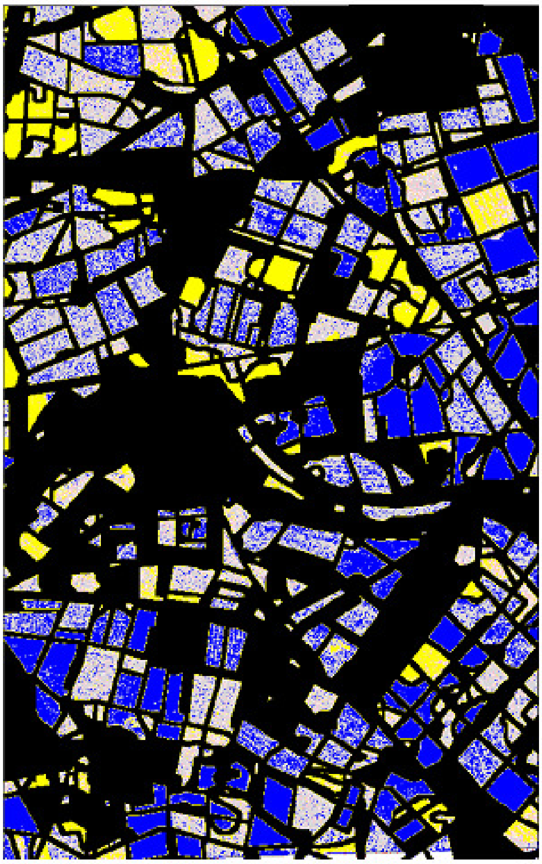

Figure 11: E-SAR and AirSAR difference image.

In general the stands that have been clear-cut between 1991-2000 can be clearly identified (Figure 11), but separation of the young and mature growth stands is more difficult. The per stand approaches (section 4.6.1-4.6.2) appear more successful than the per-pixel difference image approach.

4.7 Comparison of lidar, radar, yield tables and ground measurements of carbon in Thetford Forest

First and last return Light Direction And Ranging (LiDAR) data were acquired by the Environment Agency over Thetford using an Airborne Laser Terrain Mapper (Optech ALTM 1210) in June 2000. Carbon content was derived using a modified version of a method previously applied to LiDAR canopy height data for deciduous woodland (Patenaude *et al.,* 2002) (section 4.2). In this case, due to differences in the LiDAR processing, the LiDAR was assumed to be estimating top height rather than mean height, so the initial stage of the process (Figure 2) was not necessary (Rowland *et al.* 2003b). The coefficients used in equation 1 where different, as they are species specific. The values used for the Corsican Pine stands at Thetford, were as follows: The biomass expansion factor (BE) was assumed to be 2.0 for conifers < 19 years old and 1.5 for conifers >=20 years following the methodology of Milne, (1992). The dry mass conversion factor (DM) was set at 0.41t/m^3, and finally, the carbon content conversion factor (CC) was assumed to be 0.5 for UK coniferous forests (Milne *et al.,* 1998). As a plantation forest, the carbon content of the understorey was assumed to be negligible in Thetford due to a program of clearance.

Comparison of the results for the stand carbon estimations using the different methodologies were very similar to those observed for the height estimates even though the conversion from height to carbon is non-linear (Figure 12a, Table 3). The lowest RMSE was obtained between the radar and the field measurements. One consequence of the non-linear relationship between tree height and carbon is that tall trees store proportionally more carbon than shorter trees. This is supported by the radar results, which achieves an accuracy equal to the LiDAR results with regard to height estimation (Figure 12a) (Rowland et al., 2003b), but performs significantly more poorly at carbon estimation (Table 3) (Figure 12b). The relatively high error in the radar height estimates beyond saturation are magnified by the non-linear relationship between tree height and carbon content, resulting in a higher error than the corresponding LiDAR estimate. This exacerbation of height errors can be seen on an individual stand basis, for example, one outlier stand was estimated at 26.3m, when the FC GIS shows it to be 12.6m, this 200% error in height was propagated through to become a 300% error in carbon content (estimated carbon of 150.98t/ha compared to 52.42t/ha). The best results achieved were between the LiDAR and the FC GIS, with a RMSE of 10.42 t/ha (Figure 12b).

Figure 12b shows that although the FC GIS/yield model data and the LiDAR data show the strongest agreement, there are still many stands where they differ. Reasons for this could be that:

- The LiDAR based estimates are correct and the FC GIS/yield model data are wrong. The FC yield models (Edwards & Christie, 1981) are empirical models based on measurements of field plots and *predict* expected growth rates. Because the models are predictions of expected behaviour, some under- or over-performance in growth rates and hence height is likely to occur. Additionally, the yield models used here depend on stand top height, the mean height of the 100 tallest trees per hectare, as a driving variable. Assuming a normal distribution of top height trees, 50 percent of the trees would be expected to exceed the mean top height of the stand. In cases of apparent overestimation it may just be that the LiDAR is detecting one of these 50 trees per hectare. As stands below 1ha were excluded from the analysis then all the stands examined would be expected to contain 50 trees or more that might exceed mean stand top height.

- The initial age in the FC yield models for Corsican Pine was between 14-20 years (stands of approximately 8m of top height) (Edwards & Christie, 1981). Thus, in order to estimate values for stands below this age/height it was necessary to extrapolate the yield models backwards. This is likely to introduce error into the FC GIS/yield model results for stands below 8m.

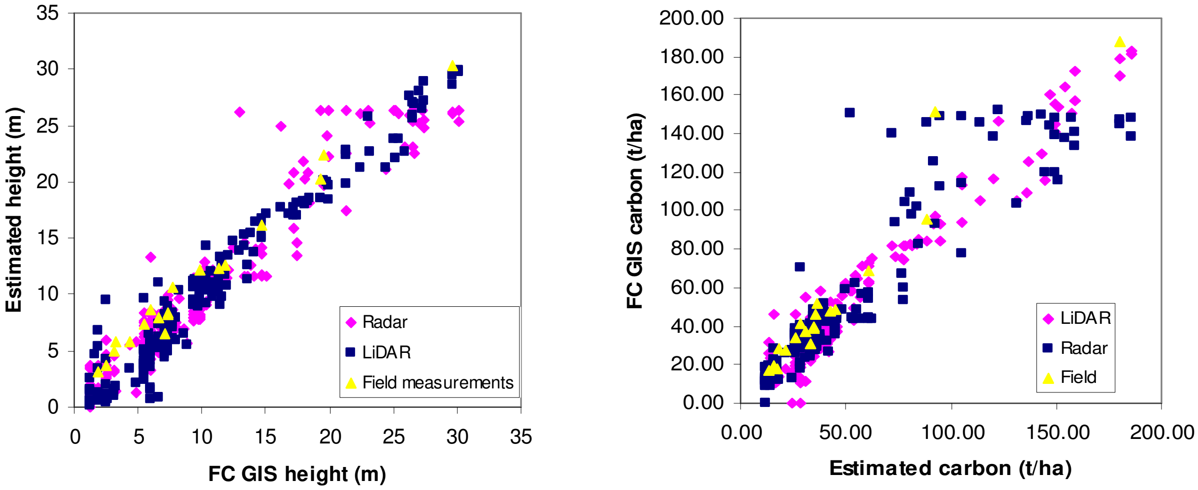

Figure 12: Comparison of estimates from LiDAR, radar, FC yield models and ground measured data for a) stand height and b) stand carbon.

Table 3. Comparison of stand carbon estimates (LiDAR, radar and FC yield) and SHAC field measurements (RMSE in t ha^{-1}, bracketed values are R^2).

	Radar	**LiDAR**	**FC Field**	**FC GIS**
FC GIS	15.20 (0.85)	10.42 (0.95)	15.57 (0.93)	--
Field	22.06 (0.79)	16.82 (0.95)	--	
LiDAR	17.68 (0.85)	--		
Radar	--			

A significant problem faced in this project was the difficulty in determining the most accurate of the methods used in the comparison of methods. Such difficulty is enhanced by the sensitivities of each approach to different canopy features, thus engendering different sources of errors. Consequently, none of the techniques can be assumed to be reliably accurate. Although some major sources of error have been identified (anomalous trees in LiDAR data, saturation point in radar data) it has not been possible to identify the most accurate method out of those compared. This validation issue remains a significant challenge faced by the remote sensing and associated scientific communities.

In summary, a number of methods for estimating stand height and deriving carbon content were tested for a coniferous forest. The results suggested that the similarity of the results from the remote sensing data, the field measurements and the FC GIS data were high. A major source of error was identified for each of the radar and the LiDAR estimates: a physical limitation (saturation of backscatter and coherence signal) and a potentially avoidable artefact of the chosen methodology in the analysis of LiDAR data respectively (further work will investigate this). However, the key strength of the LiDAR data over the radar (based on the methods applied here) was that the LiDAR produces a direct measurement of height difference between the first and last return. Conversely, the radar analysis in this report was based on a multivariate empirical relationship. Such an approach is not transferable to other sites without *a priori* ground data needed for calibration.

The comparison of the LiDAR and radar results highlighted the fact that in order for carbon content to be assessed from tree height, this variable must be assessed with a high accuracy. Accurate estimates are crucial, in particular for taller trees, which contain most of the carbon. The error in height estimation will propagate exponentially based upon the non-linear height-carbon relationship. For example, a 0.5m height error in a 2m tall tree will produce a smaller resulting carbon content error than a 0.5m height error in a 20m tree.

5. Operational missions

5.1 L-band imaging radar

At the current time there are no spaceborne L-band radar imaging sensors. Satellites carrying L-band radar sensors planned for the future including the Japanese ALOS satellite (As at April 2003, scheduled to be launched in 2004) and TerraSAR (scheduled to be launched in 2006).

The Advanced Land Observing Satellite (ALOS) is a Satellite following the Japanese Earth Resources Satellite-1 (JERS-1) and Advanced Earth Observing Satellite (ADEOS). Onboard ALOS will be a Phased Array type L-band Synthetic Aperture Radar (PALSAR). The PALSAR is an active microwave sensor for cloud-free and day-and-night land observation and provides higher performance than the JERS-1's SAR. The sensor has a beam steerable in elevation and the ScanSAR mode, which provides a wider swath than conventional SARs. The development of the PALSAR is a joint project between NASDA and Japan Resources Observation System Organization (JAROS), see http://www.nasda.go.jp/projects/sat/alos/index_e.html for further details. The Canadian Space Agency (CSA) is also currently involved in the development of active membrane antenna technology for SAR applications. To qualify this new technology, it is proposed to develop a small satellite L-band SAR demonstrator. Such a demonstrator could be placed on the same orbit as the ALOS satellite for a tandem interferometric mission.

The InfoTerra / TerraSAR programme was proposed as an early element of the ESA Earthwatch initiative. The TerraSAR mission is to make near-simultaneous observations of the Earth in high spatial resolution up to 1 m in X-band and with full polarimetry and high radiometric resolution in L-band to permit detailed and thematic information under all weather conditions on a global basis. According to the present planning, the first two satellites: TerraSAR-L1 and TerraSAR-X1 are envisaged to be installed by 2007, with an operational life-time of 5 years. Replenishment of the space segment by TerraSAR-2 satellites is scheduled for 2010. Continuity of geo-information products and services will be secured by a next generation TerraSAR-3 system, which is expected to be operational from 2015 onwards.

5.2 The NASA Earth System Science Pathfinder (ESSP) - Vegetation Canopy Lidar (VCL)

The Vegetation Canopy Lidar (VCL) is the first selected mission of the NASA Earth System Science Pathfinder (ESSP) program. The principal goal of the VCL is the characterization of the three-dimensional structure of the Earth through measurements of canopy vertical and horizontal structure and land surface topography. VCL is an active remote sensing mission using Lidar (Light Detection and Ranging) technology. Built around the Multi-Beam Laser Altimeter (MBLA), the three-beam instrument provides a 25 m contiguous along track resolution with a swath width of 8 km. It is expected to provide a vegetation canopy top height accuracy and ground surface elevation estimates of ±1 m. The launch of the VCL was previously scheduled for launch in 2003 on board an Athena launch vehicle. The launch of the mission is now, however uncertain at the current time.

6. Assessment of Project results from an end-user perspective

6.1 SGS.

Gareth Phillips, SGS (Société Générale de Surveillance) UK Ltd

SGS is acting as Designated Operational Entity for the validation and verification of Clean Development Mechanisms (CDM) and Joint Implementation (JI) projects and is also interested in offering services to verify corporate or national inventories. Tools that facilitate the verification of carbon stocks are therefore of interest to SGS.

SGS has been offered access to remotely sensed information on several occasions before and during the course of this project, but has always been sceptical as to accuracy and reliability of the data. The results of these studies have supported this scepticism but also highlighted how and where such techniques might be used and what problems still need to be overcome.

In particular:

- It is clear that remotely sensed data can be used to determine land use change from non-forest to forest and from forest to non-forest. This information can be very useful for situations where project developers are planting forests and where existing forests are either being destroyed or protected from destruction. Historic data may also become increasingly important to show previous land use and trends in land use change.

- The use of remotely sensed data to determine carbon content, directly or indirectly, remains a realistic goal. The application of the LIDAR technique to even aged plantations where growth and yield models are available could be of commercial interest in the short to medium term.

- The use of remotely sensed data to estimate change in height or above ground biomass (either directly or through relationships with height) is obviously the most valuable use of these technologies but it would appear that the current uncertainties will mask changes in slower growing forests / plantations. The technology might be applicable in faster growing plantations with less variation.

At present the results show that there is no immediate commercially useable product arising from this research. The results confirm that remote sensing is not a technique on which verifiers can yet rely and consequently, costs of verification need to be based on conventional fieldwork methods.

This is a positive finding that will facilitate greater certainty in the prediction of costs and discourage both project developers and verifiers from making unrealistic projections. The findings will also serve as a basis against which to compare similar technologies developed by other competitors.

Gareth Phillips, 18-11-2002

6.2 Ecosecurities

Jan Fehse and Louise Aukland, Ecosecurities Ltd

EcoSecurities is a private consultancy and finance company, which specializes in helping project developers to take all the necessary steps and fulfil the requirements to be internationally recognized as a carbon offset project and eventually sell their so-called ‘carbon credits’ on the market. We offer this service to projects in both the forestry and energy sectors. The project results are of direct interest to our advisory work to clients.

Potential uses of the project results

Project monitoring

One of the requirements for projects under the Kyoto Protocol’s flexible mechanisms is that they should monitor the real carbon offsets achieved during their implementation phase. In the forestry sector this inevitably faces the problem of scale: how does one measure the carbon content of a whole forest, let alone one that is composed of stands with different ages and is spread out over hundreds or thousands of hectares? Some projects may involve many landowners and may be spread out in smaller plots across an entire region or country. The exact measurement of all trees in the project is impossible and extrapolation of the results of sample measurements to the entire project is therefore a necessity.

Remote sensing techniques are a very promising tool to facilitate this extrapolation. In order to be able to extrapolate one has not only to know whether the planted forests are still there, but also in which state they are. This would, for example, prevent the extrapolation of sample measurements from a healthy, well performing stand to a stand plagued by disease. It is especially in this quantitative approach that remote sensing techniques, and especially radar technology for its ability to provide information on stand height and volume, can potentially play an important role in project monitoring,

National inventories

All countries that are a party to the Kyoto Protocol need to regularly perform a national inventory of their greenhouse gas emission sources and sinks. This includes the carbon content of the standing vegetation of the country. Clearly the use of remote sensing technology that is able to assess biomass, or parameters that allow the calculation of biomass content, such as standing volume, have a great potential to facilitate the forestry part of this inventory.

Development of standardized quantifications for projects

A requirement for the development of projects under the Kyoto Protocol’s flexible mechanisms is that they produce a sound estimate of the expected carbon offsets that the project will generate in its implementation phase . This estimate consists of the modelling of the dynamics of carbon in the forest system over time and requires a considerable amount of expert knowledge and data specific to the system. Inevitably this quantification will be quite costly and, especially in developing countries, can be a significant hurdle for the development of projects. Governments of such countries are interested in developing standardized quantifications, which would mean that ready-made models exist for the most common forestry practices in the general climatic and biophysical zones of the country. Remote sensing techniques than enable the assessment of forest height and volume will be very useful in the development of these standardized models, because they can indicate how abundant a particular forestry practice is and how homogeneously it behaves in a certain region. In other words, they can answer the questions: 1) which are the most common forestry practices in the country, where are they located and what is their volume?, and 2) how well does a certain standardized model, which will be derived from a limited set of sample data, represent reality?

Applicability of the Project results to the uses mentioned above

Tree height and volume estimation using E-SAR/AirSAR data (Section 4.5)

The results do not seem to reach very high accuracy on first sight, with standard errors of at least 2.5 m. However, the main portion of these relatively high errors seems to be caused by the inability of the radar sensors to accurately estimate the height of stands with ages above 15 years. Below this age the accuracy seems to be much higher.

For some of the uses of radar technology mentioned above the inaccuracy at higher stand ages will be a serious problem, particularly for the national inventories and the calibration of standardized models for the carbon dynamics in forest systems. But it is not of so much consequence for the monitoring of projects, especially not for those in tropical regions, since many of the tree species used in tropical forestry have rotations ranging between 10 and 25 years most of the actual monitoring time required falls within the first 15 year higher accuracy period. Beyond this period perhaps other remote sensing techniques could be used in the future.

Change in physiological parameters using multitemporal E-SAR/AirSAR data (Section 4.6)

The results presented on this aspect seem to be rather poor, which is mostly blamed on the high standard error in height determination by the sensors, which is greater than the actual height increase that can be expected to occur in British forests in a 10 year period. This is a pity, since monitoring of forest growth will have to be done more frequently than once every 10 years. Nevertheless, if only the more accurate period of 0-15 years were considered it still could be a valuable technique in the case of projects in the tropics, where trees grow much faster than in Britain.

Forest height and biomass estimation using LiDAR data (Section 4.4 & 4.7)

The results presented for the use of LiDAR derived forest height data for the estimation of forest biomass seem to be very promising for all applications described above. However, since this sensor is airborne and not spaceborne it seems to be of particular interest to project monitoring and less to national or regional surveys.

Costs vs. benefits

The use of remote sensing techniques can make forest carbon inventories and monitoring programmes easier and more time-efficient, but not without a cost. Radar images are expensive, and probably even more so if they are taken with air-borne sensors rather than space-borne. Before employing such technologies for the uses described above an assessment of costs and benefits will have to be conducted first.

For most countries wishing to conduct an inventory, and particularly for the larger ones, covering all their forests with radar data will require an immense number of images and therefore a great cost. It may be that developed countries like the UK can bear this cost, but it is unlikely that developing countries will be able to do so.

Projects in the forestry sector are generally facing financial returns that are near or under the mark of being commercially attractive. Carbon credits can increase these returns, but not if the costs of development and monitoring of a carbon project put too much strain on this benefit. Relatively expensive monitoring technologies such as radar will therefore only be an option for larger and widespread projects, such as umbrella schemes with smaller land-owners. Several of these schemas are currently under development.

It is clear that any assessment of the usefulness to end-users of the radar techniques researched in this project will only be complete if it is combined with a cost analysis.

Conclusions and recommendations

The results of this project indicate that radar remote sensing can have a great potential for measuring carbon stocks in forests, particularly of younger age, with a relatively high accuracy. However, they also show that the technologies and data-analysis methodologies will need to be further researched and developed in order to make them applicable for end-users. It would also be of great use if parallel research would be aimed at tropical forests.

An important factor in the applicability of the technologies presented here is their cost-effectiveness for each particular use: national inventories, project monitoring and the development of standardized models. We recommend that an analysis of costs and benefits should form part of any further research.

Jan Fehse and Louise Aukland, 21-11-2002.

6.3 Usefulness of Remote Sensing methods to preparation of UK Land-Use Change and Forestry (LUCF) greenhouse gas (GHG) Inventories

Dr. R. Milne, Centre for Ecology & Hydrology, Bush Estate, Edinburgh.

- At present remotely sensed (RS) data is not being used directly for preparing LUCF GHG Inventories for the UK.
- The Landsat Thematic Mapper based Land Cover map prepared by Centre for Ecology and Hydrology (CEH) in parallel with the 1990 Countryside Survey has been used to provide land cover/use data for classification of soils in relation to carbon content.
- The Landsat Thematic Mapper based Land Cover maps prepared by CEH in parallel with the 1990 and 1998 (known as 2000) Countryside Surveys are presently being investigated for use in preparing land use change matrices at scales below the individual UK regional scale e.g. at 20 km.
- Possible further use of RS is likely to build out from these applications.
- Use of RS data to drive or control mathematical models of uptake and loss of GHGs by ecosystems is likely to be useful in the future for comparison with estimates from simpler methods.
- Given this background the LINK Carbon Offset Verification programme can be seen as a useful step along the path to using RS more extensively.
- In particular the work on using both radar and LiDAR to describe biomass stock and change in forests has been notable.

- Airborne Lidar to estimate tree height, and hence biomass stock, appears to be the technique closest to becoming a useful operational tool. Repeat aerial survey of sample forests, and other land uses, would be the next stage to assessing the potential of the technique for verification of biomass/carbon stock changes.

- Hyperspectral data from airborne sensors also look to have potential for assessing biomass in mixed species forests.

- My conclusion is therefore that further data derived from airborne systems for a range of sample locations in the UK is needed. This will allow the development of interpretation and parameterisation methods as a stepping stone to the time when similar instruments are space borne and data can be obtained over the whole country.

Dr. R. Milne, 2/12/02

7. Benefit to Industrial Partners

There are no immediate plans for commercial exploitation of SAR techniques for the monitoring of forests as explored by this project. This is primarily due to the limited availability of SAR data at the appropriate wavelengths and polarization, which have been identified as being of greatest value in retrieving biomass and stem volume to facilitate a fully-accountable carbon offset verification of forests. However, a number of new satellite SAR sensor technologies are due for launch in the medium term (3-10 years), which will provide appropriate data streams on continental to global scales. The legacy of the Carbon Offset Verification program has been the development of a number of new research directions and collaborations to be able to take advantage of these sensors when launched.

In the short term, SGS has stressed the importance of land cover and land cover change as one of the key inputs from remote sensing. The results and analysis presented in section 4.6.3 (AirSAR and E-SAR difference image) demonstrates a useful contribution to this important area of verification. The identification of stand changes, such as clear-cutting and replantation has significant implications in the allocation of land-use classification. As identified by the Intergovermental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land Use Change and Forestry, discrimination between deforestation (permanent loss of forest as a result of conversion to grassland or agriculture) and forest harvesting (temporary removal of trees) will be a critical factor in allocation of land-use/land-cover to a specific carbon category. The results of section 4.6.3, together with the potential information provided by the Freeman-Durden decomposition of the scattering attributed to volume, surface and double-bounce mechanisms establishes a robust approach to identifying significant change in forest status. This work supports that of Kaisischke *et al.* (1997) and Rignot *et al.* (1994) (reported in Balzter *et al.*, 2002) who concluded that multichannel radar data, because of their sensitivity to variations in the structure of the vegetation canopy and the moisture status of the ground and vegetation layers, provide a means to classify land cover patterns and detect land cover change.

SGS currently undertakes the verification of several landuse based projects including seven projects based on extensive afforestation in remote areas in Uganda, Tanzania, Ecuador, Czech Republic, Netherlands and Malaysia. Remotely sensed data will definitely support the verification of the establishment and continued presence of the forests, and (through a time series) the age of the forest. This will provide valuable information to feed into models that may be sufficiently precise to confirm the presence or absence of carbon stocks within acceptable confidence limits.

Depending on the demand for verification services in the land use sector (which will depend on the rules relating to LULUCF decided at CoP9 in 2003), SGS may be interested in further collaboration on this topic.

8. Future Plans

A number of on-going research tasks are continuing under the LINK Carbon Offset project. In addition, a number of new programs are taking this research forward. The Environmental Change Institute (Genevieve Patenaude and Terry Dawson) are investigating the use of ecological process-based models for estimating productivity and carbon sequestration using Thetford Forest as a case study site. This work will form part of Genevieve's D.Phil. research thesis, which is expected to be completed in December 2003, and forms part of the existing project. Dr. Terry Dawson has applied for a NERC small grant to investigate the seasonal dynamics of a temperate, deciduous woodland and to relate the changes in LAI, leaf chlorophyll content and photosynthetic efficiency, as measured in the field, with hyperspectral imagery observed by the MERIS sensor. This work, if funded, will be in collaboration with Dr. Caroline Nichols (University of Edinburgh) and Dr. Mike Morecroft (CEH, Wytham Woods).

In 2001, an associated research program was launched: CORSAR (Carbon Observation and Retrieval using Synthetic Aperture Radar) with Dr. Paul Saich (University College London) as Principal Investigator and Dr. Heiko Balzter and Dr. Terry Dawson as Co-Investigator and named Collaborator respectively. The objective of the NERC-funded CORSAR project is to rigorously examine polarimetric decomposition and polarimetric SAR interferometry methods for estimating and accounting for canopy structure in biomass-backscatter relationships. This will be addressed by using a combination of coherent backscatter and radiative transfer modelling techniques (using the CASM and RT2 models), controlled experiments in an anechoic chamber at the GB-SAR facility at the University of Sheffield and exploitation of the polarimetric InSAR data acquired over Thetford Forest and Monks Wood under the NERC-BNSC SAR and Hyperspectral Airborne Campaign (SHAC) and over Duke Forest by the Space Shuttle "Endeavor" during the SIR-C mission. This work will be conducted until September 2004.

Dr. Heiko Balzter, CEH, is a Co-Investigator on the EU 5th framework project: SIBERIA-II: Multi-Sensor Concepts for Greenhouse Gas Accounting of Northern Eurasia, which started in 2002. The scientific objective of this 3-year project is to integrate Earth observation, including polarimetric and interferometry SAR methods, and climate models such that a full account of the budget of carbon within a significant part of the biosphere may be quantified. Dr. Clare Rowland has recently joined CEH to support this research.

In 2002, two NERC Centres of Excellence were launched whereby the existing academic partners of this LINK project will play a role. Dr. Terry Dawson is a member of the scientific advisory committee for the NERC Centre of Excellence in Terrestrial Carbon Dynamics (CTCD) led by Professor Shaun Quegan (University of Sheffield). The mission of CTCD is to integrate models and observations of carbon processes in a framework permitting the uncertainties in the evolving terrestrial carbon cycle to be quantified and reduced. The CTCD will undertake a comprehensive approach to understanding the role of terrestrial systems in the carbon cycle, involving state-of-the-art ecosystem models, investigation of key ecological processes, data from EO sensors and other data sources and advanced methods of modelling uncertainty. The aim is to quantify carbon fluxes and their uncertainties at local, regional and continental scales, and to devise methodological, data and instrument advances to reduce these uncertainties. The CLASSIC (Climate and Land Surface Systems Interaction Centre of Excellence (Professor Mike Barnsley, University of Wales, Swansea) involves Dr. Adrian Luckman and Dr. Heiko Balzter as Co-Investigators. This programme will undertake fundamental research, exploiting satellite-sensor data, to improve the representation of coupled land-surface and atmospheric processes, and via the development of enhanced climate and land-surface process models.

9. Concluding remarks

A summary of the significant outcomes from this project to date are:

- There is a saturation problem that limits our ability to retrieve biophysical variables such as biomass, timber volume, age or height from radar intensity images in mature stands of trees. The best performances were achieved through a cross-polarized sensor (HV) at the lower frequencies, such as the L-, or better, P-band. However, the use of temporal or spatial coherence data may extend the dynamic range somewhat, but further research is needed to support this thesis.

- The accuracy of the height retrievals are the equivalent of several metres rms height error when estimated across a sample which includes a mixture of both saturated and non-saturated stands.

- Changes in timber volume / age / height can be measured accurately over a 9 year interval for young stands, but accuracy decreases as the stands mature.

- New growth or clear-cutting can readily be identified in L-band radar imagery.

- Neural networks are a useful technique for exploring noisy data sets especially when multiple input variables are used as they are capable of identifying relationships at the highest accuracy (i.e. lowest RMSE against a test data set). This is a result of their ability to define complex non-linear associations between input and output data. However, they are subject to overtraining, especially in limited data sets, and are effectively a 'black-box' model, providing no understanding of the underlying physical or biophysical mechanisms in our applications.

- Current airborne lidar can measure tree heights with sufficient accuracy to have potential as an input to estimates of above-ground biomass, but there remains a need to examine how remote sensing can effectively provide information on species composition.

- The use of remote sensing for carbon accounting in general is constrained by the lack of data on growth patterns, yield models etc. In particular, yield models only have data from 5 years prior to the first thinning event. The time of this first thinning varies slightly depending on yield class and species, but most of the yield curves only start at around 20 years. In this study, we extrapolated the yield curves back to get estimates of tree height and volume for stands less than 20 years old. The availability of ground-measured validation data remains a significant issue in natural and unmanaged forest ecosystems.

The comments from the end-users perspective have highlighted a number of research issues, which remain. In particular, relating to the SAR evaluation, the key limitation in this project has been the variability in canopy structure, which causes signal saturation and large scatter of radar backscatter. A substantial part of the problem of defining retrieval algorithms for forest biomass is that radar responds to the shapes, sizes, orientations and dielectric properties of all of the scatterers that are illuminated (including the ground). Microwave backscatter models have revealed that the effect of variation in canopy structure on the signal can be higher than the effect of biomass, and the CORSAR project will attempt to quantify some of these effects. Although not specifically investigated in this project, the new technique of polarimetric SAR interferometry also potentially offers a means of improving SAR-based estimates of forest biomass by measuring canopy structural variability. The polarisation information is dependent on the underlying scattering mechanism, and the interferometric information can be used to determine the vertical location of these scattering events in the canopy.

From the end-user perspectives, the LIDAR evaluation research presented the most promising outcome. The NASA Vegetation Canopy Lidar programme and the global mission is expected to measure both elevation and canopy heights to an accuracy of ±1 m, but a launch date for this mission remains uncertain. Coupled with the methodology presented in this report, it provides an exciting potential to estimate biomass and carbon stocks of tropical and temperate forests operationally in support of the carbon trading schemes in which Ecosecurities and SGS will need to administer.

One of the end-users raised the issue of costs associated with using remote sensing methods as compared with field-based and modelling techniques for forest carbon assessments. Although this issue is outside of the terms of reference for this project, the space industry is under increasing pressure from Government to recover costs from Earth Observation (EO) data and products. The provision of competitively-priced EO-based products will therefore be crucial to enable the successful take-up of remote sensing technology by the commercial sector.

Finally, there is more research needed in the integration and synergy of multiple sensors (especially radar and optical), together with models to constrain and improve estimates of biophysical variables of interest to those evaluating productivity, biomass and carbon storage in forest ecosystems. The recent and on-going research projects mentioned in the preceding section will make attempts to investigate this area.

10. Acknowledgements

The project team thanks Ralph Cordey (BAe Systems), Geoff Wadge, Susanne Mecklenburg (NERC) and Steven Wilson (BNSC) for their valuable comments at the final meeting, held on 5 December 2002 at BNSC Headquarters London and on an earlier draft of this report, and to Claudia Stein (NERC) for her patience and efficiency for chasing up this report.

T. P. Dawson, 21st July 2003.

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