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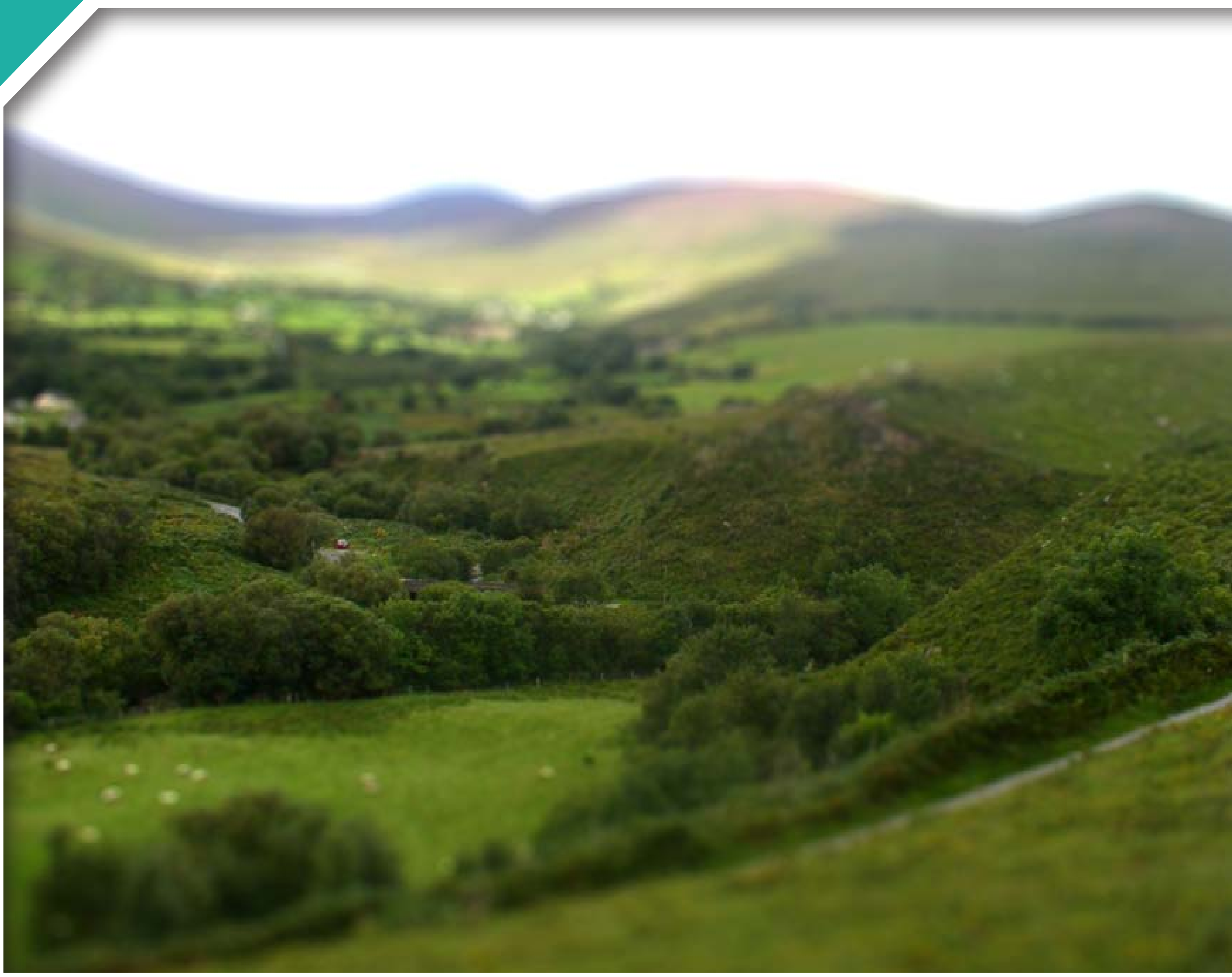
BRIAR: Biomass Retrieval in Ireland using Active Remote sensing

Authors: Stuart Green, Shafique Martin, Saeid Gharechelou, Fiona Cawkwell and Kevin Black



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EPA RESEARCH PROGRAMME 2014–2020

BRIAR: Biomass Retrieval in Ireland Using Active Remote Sensing

(2014-CCRP-MS.17)

Prepared for the Environmental Protection Agency

by

Teagasc

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Biomass Retrieval Using Active Remote Sensing

Hedgerows are a very significant component of the Irish landscape. They perform multiple functions, acting as boundary markers, acting as stock-proof fencing, supporting bio-diversity and controlling run-off. They function as reservoirs of above-ground biomass and their potential as carbon sinks was explored in an earlier study which found that hedgerows potentially sequester 0.5–2.7 tCO_2/ha/year.

The earlier study used light detection and ranging (lidar) scanning to build 3D models of hedgerows to successfully estimate biomass, but at the time the cost–benefit of doing so was poor. However, this has since changed with the availability of free lidar sources and the reduced cost of commissioning/acquiring lidar data. The purpose of the present study was to examine the use of another active remote sensing tool, imaging radar, to estimate biomass in hedgerows.

The study area around Fermoy in County Cork was field surveyed using new drone technology to collect data on a sample of hedgerows from which estimates of biomass could be drawn. These field estimates were used with new high-resolution TerraSAR-X Staring Spotlight (TSX-SS) radar imagery to model hedgerows directly from radar backscatter.

The study found that hedgerow biomass cannot be derived directly from radar backscatter. There were a number of reasons for this, such as the hedgerow biomass density, with an average of 10 kg/m^2, being above the threshold of saturation for radar in the X-band frequency range. However, other radar sensors with lower frequencies, and thus higher saturation limits, do not have the spatial resolution to map hedgerows.

An alternative method of investigating hedgerow structure, and thus inferring biomass, interferometry, is not successful as the level of coherence between the observations in our dataset was too low to build a 3D model (i.e. the backscatter from the hedgerow changed too much between observations).

A new method that examines the cross-sectional response of the radar return across a hedgerow was shown to be successful at modelling the relationship between the width of the backscatter profile and the width of the hedgerow. However, this too was sensitive to the orientation of the hedgerow to the sensor.

Therefore, this study shows that radar data does not seem to be an appropriate technology for estimating hedgerow properties in Ireland.

In order to estimate the national stock of hedgerow, the new Prime2 spatial data storage model (OSI, 2014) was applied in conjunction with developed maps showing the probability of a field boundary being a stone wall or a hedgerow, to give a new national estimate for hedgerow length in Ireland of 689,000 km. This estimate is double the frequently quoted figure of 300,000 km because of a much wider definition of “hedgerow” used in this report.

Net change in hedgerow length was examined using the aerial photographic records from 1995, 2005 and 2015, along with county-level survey records, showing that there has been a net removal of hedgerows between 1995 and 2015 of between 0.16% and 0.3% per annum, although the rate is much slower in the latter half of that period.

As X-band radar seems to be inappropriate for hedgerow evaluation (especially for the obvious case of the identification of the complete removal of large hedgerows, for which it is much more expensive and time-consuming than the detection of hedgerow removal using aerial photography), the existing national lidar surveys from the Geological Survey of Ireland were examined for their appropriateness for hedgerow evaluation. A digital canopy model derived from these data successfully estimated heights (mean and maximum) in the trial test site, with an r^2 value of 0.79.

Recommendations

- A national point cloud-based inventory of hedgerows should be commissioned and repeated at 5-yearly intervals.

- The quickest and cheapest approach is to use the Ordnance Survey Ireland proposed 25 cm photogrammetric point cloud (as a lidar proxy) to perform a national 1 km sample survey, in the same way as for published county surveys.
- Studies on the sequestration difference between managed and unmanaged hedges should be undertaken (including life-cycle analysis on the fate of biomass removed during management).
- Field experiments need to be undertaken to measure directly the carbon stock through destructive testing of the biomass in hedgerows.
- Consideration should be given to the carbon stored in the bank (on which the hedgerow is planted), as it is a man-made object that is removed whenever a hedgerow is removed.

1 Introduction

1.1 Hedgerows in Ireland

Hedgerows are an important feature of the Irish pastoral landscape. Hedgerows have developed multifunctional roles as landscape features and reservoirs of biodiversity, in controlling factors in surface hydrology and, as highlighted in this report, potentially in carbon sequestration, and in these roles the hedgerow structure and composition are as important as location (Benhamou *et al*., 2013). The fact that hedgerows are a store of carbon in above-ground biomass (AGB) (the amount of dry living material present, expressed in tonnes/ha) is understood. What is not known is the total reservoir of biomass in the national hedgerow stock, the year-on-year change in hedgerow stock and the difference in biomass accumulation between managed and unmanaged hedgerows.

The use of lidar technology to estimate AGB in hedgerows was examined in an earlier Environmental Protection Agency (EPA)-funded project: Carbon Sequestration by Hedgerows in the Irish Landscape – Towards a National Hedgerow Biomass Inventory for the LULUCF Sector Using LiDAR Remote Sensing (Black *et al*., 2014).

In this earlier study the capacity for the national hedgerow stock to sequester carbon and to thus have a beneficial impact on Ireland's greenhouse gas emissions was estimated (Table 1.1). This study investigated the technical capacity of lidar and showed that it could measure the AGB of hedgerows very well. However, the cost–benefit analysis of a national hedgerow biomass survey compared with the value of the carbon sequestered showed that, at the then-current European Trading Scheme (ETS) carbon price per tonne, and considering what was known about the net removal rate of hedgerows, a lidar survey national programme was not justified.

However, the potential size of the carbon reservoir in the national hedgerow stock was of sufficient magnitude that other methods of estimation should be investigated. One potential technology is high-resolution radar imaging.

1.2 Radar Remote Sensing

Radar satellites differ from the more familiar optical satellites in a number of very significant ways. Radar images are constructed by recording the magnitude and phase (the timing component of the signal) of reflected microwave signals generated by the satellite itself – it is an active sensor compared with the passive recording of reflected sunlight in an optical system. If the analogy of the optical system is the eye, then the analogy of the radar is the ear.

Many optical systems today record across a wide spectrum of reflected light, utilising many channels (or bands) of information to create an image, but the radar system generates a signal at a single wavelength and records the amplitude, phase and polarity of the return, and thus provides far less information (Figure 1.1).

The returned signal is a function of the roughness and electrical conductivity of the target, as well as the geometric relationship between the target and

Table 1.1. Estimate of hedgerow biomass sequestration

Sequestration source	Estimate	Lower/upper limit of estimate
Above-ground hedgerow sequestration rate (tCO_2/ha/year)	1.6	0.5–2.7
Total hedgerow sequestration rate (tCO_2/ha/year)	1.9	0.6–3.2
Above-ground scrub sequestration rate (tCO_2/ha/year)	2.6	2.2–2.8
Total scrub sequestration rate (tCO_2/ha/year)	3.1	2.7–3.4
National hedge and scrub annual sequestration (MtCO_2)	0.7	0.3–1.1
Annual net–net removal (tCO_2)	9200	3000–17000

Source: adapted from Black *et al*. (2014).

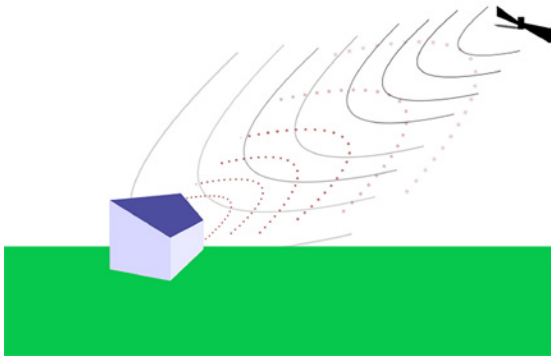


Figure 1.1. Schematic showing radar signal return.

the satellite. Radar has two advantages over passive optical systems:

1. the microwave signal generated penetrates clouds so an image can be acquired in most conditions;
2. the microwaves are able to penetrate into the target to some degree (depending on wavelength).

Figure 1.2 shows a false colour composite of three TerraSAR-X radar images captured on three dates in 2015 over Fermoy in County Cork. The different colours represent the different intensity of returns on the dates (as a result of soil differences, crop growth or grazing effects). Bright targets have a strong response and may be saturated (i.e. have reached the upper limit of the sensor); dark targets are either in shadow (where an object blocked the radar signal) or very smooth (low texture) and so the signal is reflected away from the sensor. Another capability of radar systems is their ability to create 3D models of the target using two methods: radargrammetry and interferometric synthetic aperture radar (InSAR). InSAR utilises the phase information to construct a digital elevation model (DEM), but is sensitive to changes between images (known as coherence). Radargrammetry, on the other hand, uses the intensity signal in a stereo-pair of radar images, as in conventional stereoscopy; however, the resulting DEMs are much coarser.

1.3 Current Status of Irish Hedgerows

Estimates of hedgerows in the Irish landscape range from 3.9% to 5% of the total land cover area (Cabot, 1999; NFI, 2007). The Teagasc Hedgerow and Scrub Map gave a national estimate of non-forest woody biomass (NFWB) of approximately 450 kha, or 6.4 % of the landscape (Green, 2011). Hedgerow stock is often given as a length and a figure of 300,000 km of hedgerow in Ireland is often quoted in the grey literature and official reports; however, the source of this estimate is not easy to identify.

A number of counties surveyed hedgerows in the mid-2000s using Heritage Council survey guidelines (Foulkes *et al*., 2013). These surveys are varied but indicate typical hedgerow densities of approximately 7 km of hedgerow every square km – or 50 m/ha – with typical estimates of 11,243 km of hedgerows in Donegal and 17,674 km in Roscommon.

Although the hedgerow stock has historically been under pressure through removal (largely through road building, housing and farm restructuring) (Lucey and Doris, 2001), hedgerows have been given some protection through designation as landscape features since 2009. In order to receive agricultural subsidies farmers have to show that they are complying with various regulations (known as “cross compliance”).

The regulations are known as Statutory Management Requirements (SMR). Following the SMR means that one maintains land in good agricultural and environmental condition (GAEC). GAEC regulations regarding hedgerows now mean that, generally, hedgerows cannot be removed and must be maintained. In practice, however, a hedgerow can be removed if a new hedgerow is pre-planted of equal length and Environmental Impact Assessment (EIA) rules are complied with (DAFM, 2016). In addition, restructuring of rural land holdings are subject to screening for possible EIA if:

Figure 1.2. TerraSAR-X radar image captured on three dates in 2015. The colours represent differences in the intensity of the returns on the three dates.

- the length of the field boundary to be removed is greater than 500 m (a cumulative length over 5 years, not just a single 500 m length); or
- the area of lands to be restructured by the removal of field boundaries is greater than 5 ha.

Approximately 50–60 screenings are processed each year by the Department of Agriculture, Food and the Marine (DAFM), nearly all of which are approved without the need for a full EIA.

However, an EIA is mandatory if:

- the length of the field boundary to be removed is greater than 2 km; or
- the area of lands to be restructured by the removal of field boundaries is greater than 50 ha.

The following are exempted activities that do not need DAFM approval:

- maintenance work on existing stone walls and hedgerows;
- removal of post and wire fencing (barbed wire or electrified wire).

If uncultivated land or semi-natural areas are to be used for intensive agriculture, they need to be screened if the area is greater than 5 ha, and an EIA is mandatory for areas above 50 ha. This can have an impact on scrub, depending on the definition used (e.g. control of invasive briars is exempt from regulation).

Analysing the records of EIA screening applications for "field boundary removal" from 2011 to 2017[1] show that 93.5% of applications were "approved", meaning that removal could proceed without the need for an EIA (Table 1.2). In total, 4.5% of applications were rejected, meaning that a full EIA would be needed if the farmer were to proceed ("other" means that an EIA was not applicable or that the application was incomplete). Taking the greater than 500 m and less than 2 km rule for EIA screening suggests that a minimum of 264 km to a maximum of 1050 km of mature hedgerow were removed over the 6 year period from 2011 to 2017. Over that period Wexford had the highest number of applications ($n = 120$) and Monaghan was the only county with zero applications for field boundary removal EIA screening.

Under the Green Low-carbon Agri-environment Scheme (GLAS), the management/planting of hedgerows is a significant feature, with farmers able to claim for the management of up to 200 m of internal hedgerows. Importantly, farm boundary hedgerows, which make up 75% of hedgerows, are not eligible as they are considered not to be under the complete

1 https://www.agriculture.gov.ie/ruralenvironmentsustainability/environmentalimpactassessment/registerofeiascreeningapplicationdecisions/ (accessed September 2019).

Table 1.2. Number of EIA screening applications for hedgerow removal

Year	EIA screening			
	Approved	Other	Rejected	Total
2011	3	–	–	3
2012	97	4	6	107
2013	75	4	1	80
2014	94	1	6	101
2015	130	1	6	137
2016	69	1	7	77
2017	60	–	–	60
Total	528	11	26	565
%	93.5	2.0	4.5	100

control of the farmer applicant (see section 1.6). In the first tranche of applications, the total length to be planted was 1300 km; figures for subsequent tranches (2 and 3) are not available, but a recent impact assessment on GLAS showed a >90% compliance rate with the laying of new hedges (Image and Brown, 2018).

Reviewing the online application figures, there is evidence of the net removal of hedgerows; however, analysis of other independent data from other sources can give us a more complete picture.

1.3.1 Definitions of hedgerows

The structural description of hedges differs according to their species composition; however, a hedge can be defined as a compact linear formation of small trees, bushes and shrubs (Black *et al.*, 2014).

Other definitions include those of Forman and Baudry (1984), who defined a hedgerow as a narrow band of woody vegetation and associated organisms that separates fields, and French and Cummins (2001), who defined a hedgerow as a combination of a hedge and a hedge-bottom supporting farming boundaries and maintaining the woody vegetation by its linear shape.

In the National Forest Inventory, woody treelines at a forest edge or in an agricultural field boundary and around settlements are named as hedgerows (Forest Service of Ireland, 2007).

As this project is concerned with biomass alone and no other aspect of hedgerow multi-functionality, within this project a broad definition of hedgerows is proposed:

> Woody field, forest or settlement boundaries, including remnant or outgrown hedgerows and treelines, and including species such as gorse, less than 10 m in width.

1.4 Aims and Objectives

In this project we examined the capabilities of new high-resolution radar satellite data to directly estimate hedgerow biomass from backscatter. The use of radar to look at biomass for small targets is an emerging field and we present the existing literature in the wider context of hedgerow measurement and mapping.

The aim of the project was to directly estimate biomass form radar backscatter in hedgerows; however, this proved not to be possible for the reasons outlined below (Chapter 5). The project has, however, developed methods to accurately detect hedgerows. New mapping sources have allowed for a more detailed and accurate estimate of the national hedgerow stock.

The report recommends the exploitation of a number of existing remote sensing datasets to yield a cost-effective estimate of hedgerow biomass for the country, along with recommendations for new field research to more accurately ascribe biomass, above and below ground, to hedgerows.

2 Review of Remote Sensing of Hedgerows

Remote sensing, or Earth observation, is the use of satellites, aircraft, drones or sensors to remotely capture information about a target. When the target is hedgerows that literature can be broadly spilt into two themes: the “detection” of hedgerows and the “characterisation” of hedgerows.

This review demonstrates that the literature is developing and shows that technology is outpacing the methodologies needed to correctly use and assess it.

2.1 Detecting Hedgerows with Earth Observation

There is a growing literature on mapping the extent of hedgerows automatically from optical imagery, either satellite, airborne or drone captured. The principal method applied is object oriented (OO) segmentation.

In segmentation, groups of contiguous pixels with similar properties are “clumped” together to create objects. Classification is then carried out on these objects rather than individual pixels (see section 5.3).

Vannier and Hubert-Moy (2010) used an OO-based method to identify and detect the hedgerow network automatically in France using a combination of Spot and Kompsat (high-resolution optical satellites). The segmentation was carried out at three hierarchical levels (tree, hedge and field) and the images were classified using fuzzy logic (an approach to computing based on “degrees of truth”). The accuracy result showed that the SPOT 5 images emerge as slightly superior to other classifications, for example small wooded elements extraction classified with 84.5% and 97% accurate detection for the Kompsat and SPOT 5 images, respectively. It was concluded that an OO approach applied to satellite images with a very high spatial resolution (VHSR) of about 1 m is a computationally efficient, reliable and valid method for detecting small wooded elements and characterising wooded hedgerows.

The UK Ordnance Survey created a Landscape Feature Layer for the National Payments Agency (Ordnance Survey, 2016). This used segmentation approaches to segment aerial imagery with respect to known digitised field boundaries. The map identified the presence of hedgerows across along the length of the digitised boundary; however, it did not measure the aerial extent of the hedgerow or the volume. There are no published statistics on the accuracy or detection limits of this method.

However, also in the UK, a national map of hedgerows was recently created using national-scale boundary maps: a digital terrain model (DTM) and a digital surface model (DSM) (Scholefield *et al*., 2016). This simple process (difference between the DTM and the DSM at a boundary) allows for the length and height of hedgerows to be estimated. This study used UK NextMAp DSM and DTM data with a 5 m resolution. In Ireland, 1 m and 2 m national DSM and DTM products are available from Bluesky.[2] The performance of the model was evaluated against existing woody linear feature data in countryside surveys across a range of scales. The results indicate that, despite some underestimation, this simple approach may provide valuable information on the extent and locations of woody linear features in the countryside at both local and national scales, and is a possible approach for use in Ireland (this approach is demonstrated in section 6.3)

Aksoy *et al*. (2010) used a multi-feature and multi-scale strategy and a shape-based target detection algorithm based on spectral and texture analysis for the discrimination of hedgerow pixels, and extracted the hedgerow network in six sites in three different countries in Europe using Quick Bird imagery. They concluded that their model met the proposed goal and that the proposed solution was generic enough for adaption to the detection of natural boundaries of linear object classes (e.g. roads, rivers, paths).

Fauvel *et al*. (2012) detected hedgerows in very-high-resolution (VHR) Worldview-2 images using feature

2 http://www.bluesky-world.ie/standard-height-data (accessed September 2019).

orientation, the normalised difference vegetation index and texture analysis in a support vector machine (SVM) analysis The results showed that the local orientation was defined as the difference between the minimum and the maximum of the morphological directional profile. The detection was performed with the support vector data description algorithm, and hedges were correctly discriminated from among other woody elements such as forests. However, false detection of non-woody elements with significant local orientation appears in the final result.

Burnett and Blaschke (2003), in a heavily cited earlier paper, applied multi-scale segmentation object relationship modelling and segmentation of colour ortho-photography to identify linear objects in the landscape. They introduced a five-step framework to address issues of heterogeneity, scale, connectivity and quasi-equilibriums in landscapes using the hierarchical patch dynamics (HPD) method. This multi-scale segmentation/object relationship approach dominates linear feature extraction methodologies.

Hedgerow maps are an important input into both large-scale ecosystem service studies and automated methods for identifying areas of high nature value (Weissteiner *et al*., 2016). A study by Sheeren *et al*. (2009) used a hybrid approach including both aerial photographs and ancillary data of coarser resolution to automatically discriminate small wooded elements. Initially, extraction of wooded elements was carried out using textural analysis. Textural analysis is mainly used to extract all of the wooded elements from orthophotos more efficiently and limit confusion with other classes that have similar pixel values (e.g. grasslands and crop fields). Compared with the traditional per-pixel classification approach, the hybrid method enables the use of spatial and relational features during the classification process. Tansey *et al*. (2009) also used OO classification of VHR airborne imagery in the UK for the extraction of hedgerows and found that not all of the criteria for defining hedgerows could be successfully determined.

Many of these object/segmentation approaches were brought together in a recent study by O'Connell *et al*. (2015), in which a rural area of the UK was mapped with high-resolution airborne data, processed, segmented and classified through a random forest model. The performance was good overall for all of the classes selected, with "hedgerow" achieving 77% production accuracy. However, the analysis in the paper is weakened by the inclusion of "shadow" as a land cover class. Although shadow is present and is extracted in the segmentation process (see section 5.3), it is not a land cover/land use. A pixel classified as shadow is an incorrect classification for a land use study; as most of these shadows are associated with hedgerows, many of the shadow points should have been classified as hedges, and therefore the true user accuracy for the hedgerow class is likely to be much lower.

The over-riding result from these studies is that the stated accuracies have to be treated with caution and that the methods do not in general identify entire hedgerows but components of hedgerows.

2.1.1 Hedgerow detection with active sensors

Malinowski (2016) successfully used a lidar dataset (DK-DEM/Point cloud) and its derivatives for identifying and delineating selected landscape elements that include hedgerows, single trees and groups of trees, stone and earth dikes, and ditches, as in the earlier EPA study (Black *et al*., 2014). Airborne laser scanning data acquired between 2014 and 2015 for the whole country of Denmark, with 0.15 m positional accuracy and 0.05 m vertical accuracy, was used to create a normalised DSM and Fieldblocks, the Danish implementation of the Land Parcel Identification System (LPIS).

Betbeder *et al*. (2014) explored the use of synthetic aperture radar (SAR) imagery to detect hedgerow networks and describe the hedgerow canopy heterogeneity using TerraSAR-X imagery. The extraction of hedgerow networks was achieved using an OO method (as outlined above) using two polarimetric parameters, the single bounce and the Shannon entropy (ShE), derived from one TerraSAR-X image. The hedgerow canopy heterogeneity estimated from field measurements was compared with two backscattering coefficients and three polarimetric parameters derived from the same image. The results show that the hedgerow network and its fragmentation can be identified with a kappa index (classification accuracy measure) of 0.92.

This high kappa value should be treated with caution, as there are questions about whether or not points provide the best samples for linear features. Accuracy was determined with regard to whether the point intersected a hedge or not, not with regard to whether or not the hedge was correctly delineated as an object. Most importantly, a 50/50 split of hedge/non-hedge is an inappropriate sampling structure as it does not reflect the true relative area coverage of hedgerows in the trial area (if hedgerows cover 5% of an area and non-hedgerows 95%, the sampling strategy should reflect this). The authors note that errors are caused by some hedgerows being below the pixel threshold and that there are layover artefacts as a result of hedge/sensor orientation. No attempt at measuring height, volume or biomass was made in this study.

Exploring some of the limitations of OO classification in the literature, a recent review of the detection of non-forest trees found that OO methods produced an output that better matched the true spatial distribution of trees (compared with visual interpretation), but that pixel-based approaches created more accurate overall cover estimates (Meneguzzo *et al.*, 2013). The authors identified the lack of an accepted accuracy method for OO approaches and recommended “targeted assessment”, looking at small sub-rates in an image to see how well the sub-map mirrors reality using patch metrics.

2.2 General Approaches to Radar Monitoring of Woody Biomass

There are a number of recent reviews of forest biomass estimation in the remote sensing literature. Lu *et al.* (2016) give a general review of all remote sensing methods, but reviews of a number of radar-specific methods have also been published (Olander *et al.*, 2008; Koch, 2010). A radar biomass review by Sinha *et. al*. (2015) gives a comprehensive overview of current systems, with particular emphasis on biomass saturation and methods to overcome it.

Literature covering the use of C-, X and L-band (differing wavelength and frequencies) radar data, from fine to coarse resolution, for forest resource monitoring and biomass retrieval is extensive, but much less research has been carried out on the use of X-band SAR data for specially examining NFWB.

In radar systems, the wavelength of the microwaves used determines the spatial and geometric properties of the resulting imagery (Table 2.1).

Forests with high AGB or a high stem volume are difficult to detect as the sensitivity of the radar backscatter to biomass saturates above a certain point (Le Toan *et al.*, 1992; Beaudoin *et al.*, 1994). The saturation level is dependent on the frequency, polarisation and incidence angle used by the sensor, in addition to the forest type, structure and moisture conditions. As a result, the observed biomass saturation limit generally varies between 20 and 200 Mg/ha for different studies (Imhoff, 1995; Saatchi *et al.*, 2007). At long wavelengths (e.g. L- or P-band), the radar signal saturates at higher biomass levels; the saturation level is much lower for radar backscatter from shorter wavelengths (the shorter wavelength X-band). As the literature shows (see Table 2.1), as the wavelength of the radar signal decreases the spatial resolution increases and thus we are able to see smaller and smaller targets. However, the level at which the signal saturates as a function of biomass decreases, thus making the sensor much less sensitive to change and variety in biomass levels of the targets.

Although much of the literature on biomass retrieval using radar is concerned with forestry, some literature does exist around mapping heterogeneous wooded landscapes that is applicable. Betbeder *et al.* (2014) used the SAR data TerraSAR-X, aerial photography and a SPOT 5 optical image for mapping species distribution in France. In this study, the authors

Table 2.1. Characteristics of different radar frequency bands

Frequency band	Wavelength (cm)	Spatial resolution (m)	Typical saturation (t/ha)
X	2.4–3.8	1	<25
C	3.8–7.5	5–10	30–100
L	15–30	10–20	100–300

focused on extracting the hedgerow network using VHR TerraSAR-X dual polarisation data (HH/VV[3]). They applied the ShE and backscattering analysis in single and double bounce for processing the OO classification and extracting the hedgerow network. The accuracy analysis of the hedgerow network showed an overall match of 92% and 90% for SPOT 5 and TerraSAR-X, respectively.

Recent work has shown that the saturation effect is not simply a result of biomass but of structure within the forest, such that knowledge of structure may allow for extraction of some biomass parameters (such as stem density) above the reported threshold levels (Joshi *et al.*, 2017).

2.3 X-band Radar in Forest Monitoring and Biomass

In recent years, the spatial and temporal resolution capabilities of radar satellite data have improved rapidly. The use of extra-high-resolution TSX-SS mode data (~0.25 m spatial resolution) will allow for better characterisation of NFWB than has been previously possible with existing sensors and modes. This will be compared with the more established imaging modes (Spotlight and Stripmap) to determine the improvements, if any, in using the higher resolution data.

The use of VHSR radar to detect hedgerows and individual trees and to measure their structure is a very recent development, but the work published has demonstrated success. Betbeder *et al.* (2014) used a similar technique as proposed in this study to look at the structure of hedgerows using TSX-SS data and concluded that "very high spatial resolution radar images can both precisely detect the presence of wooded hedgerow networks and characterize their structure". The data that we plan to use are of an order of magnitude higher resolution than those used by Betbeder *et al*. (2014).

Working with vegetative targets, the literature strongly suggests that, when using radargrammetry approaches to estimate elevation data, coherence is unlikely to be achieved (Ali *et al.*, 2017).

2.4 X-band Uses for Non-forest Woody Biomass

The literature on scrub/hedgerow mapping with X-band data is small (approximately 110+ papers) but growing. Some insights can be gained by looking at the literature on mapping savannah woodlands. These semi-arid habitats, although quite different from Irish conditions, do present some aspects of NFWB mapping.

One observation, demonstrated in experiments, is that the scattering centre (the apparent source of volumetric scattering in a woodland) is lower because of a larger ground component, and this is increased with the use of high-resolution X-band data (Viergever *et al.*, 2007).

This sensitivity to ground signals may explain why a number of studies have shown that L-band data are better at mapping cover and AGB in bare savannah woodlands than X-band data/approaches (Naidoo *et al*., 2015).

Indeed, one of the principal issues identified with mapping heterogeneous or sparsely wooded landscape is the confusion of backscatter signals from other components in the landscape (Viergever, 2008). These effects can be mitigated by choosing the correct retrieval algorithm (Lamsal *et al.*, 2012), improving spatial resolution and using a priori data on the spatial distribution of the target.

VHSR X-band backscatter imagery has been shown to very successfully map hedgerows within a conventional image classification schema. Betbeder *et al.* (2015) used TerraSAR-X HH/VV (polarisation) imagery in an OO classification approach, with a 90–92% extraction accuracy for hedgerows (it is worth noting that this is the same data source used in this study).

2.4.1 Hedgerow biomass estimation using X-band data

At X-band, the use of above-ground elevation data derived from stereo SAR data has shown potential for application in the estimation of forest biomass (Perko

3 The signal from some SAR sensors is polarised as either (H)orizontal or (V)ertical. The returning signal is also polarised – when examining the results there are four possible combinations: H out and H back (HH), H out and V back (HV), V out and V back (VV), V out and H back (VH).

et al., 2010; Karjalainen *et al.*, 2012). Information on the vegetation height is extracted by calculating the difference between the radar-extracted elevation values and the ground surface elevations from an existing DTM.

It has long been recognised that laser scanning, lidar, can be a useful tool in national biomass inventories (Brown, 2002) and is well regarded for carbon reporting (Patenaude *et al.*, 2005). However, as the system has to be mounted on an aircraft, cost remains a barrier to its operational use (McRoberts *et al.*, 2010). The experimental space-borne laser scanner, GLAS, has been used for biomass retrieval (Sun *et al.*, 2008), but its footprint size and acquisition geometry make it inappropriate for use in fragmented landscapes such as in Ireland.

Lidar was used successfully in a study conducted by some members of this consortium (EPA project 2010-CCRP-DS-1.1, Black *et al.*, 2014). The project successfully estimated biomass in hedgerows using high-resolution airborne lidar. Direct modelling of lidar metrics, such as intensity and percentiles of first and second laser returns, were used to accurately (root mean square error or RMSE: ±7.3–19 tC/ha) estimate hedgerow biomass and NFWB. Estimates suggest that hedgerow and non-forest woodlands could potentially sequester 0.66–3.3 tCO_2/ha/year. However, NFWB outside hedgerows was not considered and the estimated cost of a national survey remains too high (Black *et al.*, 2014).

Remote sensing SAR methods for detecting AGB in forest ecosystems are commonplace, although have limitations (see Sinha *et al.*, 2015 for a recent review), although these are fewer than for NFWB.

Most articles on forest biomass and forest resource characterisation use SAR in the C- and L-band, with fewer using X-band SAR data because of the limitation of penetration in the forest canopy. Therefore, for this study on NFWB specifically in hedgerow and scrub biomass retrieval using TerraSAR-X data, there is limited information in the literature. Basically, for the use of SAR data in forest AGB, three general approaches are used: backscatter, coherence and phase based. However, to begin with we introduce the approaches from the full radar biomass literature.

The most common approach is to relate backscatter to stand parameters collected in the field [such as diameter at breast height (DBH), height, stem volume] through a statistical relationship with the backscattering intensity of radar data and field observation records to retrieve the biomass derived from the stem measurements. The most common regression models in statistical relationship research have been parametric (e.g. regression) models and non-parametric (e.g. decision tree) models (Latifi *et al.*, 2010; Morel *et al.*, 2012; Güneralp *et al.*, 2014). In more recent years, more flexible methods have been used for identifying the biophysical relationship, such as AGB and remote sensing data. Machine learning methods have a higher potential than standard regression models because of the ability to identify complex non-linear relationships between response and predictor variables, such as K-nearest neighbour (KNN), SVM and back propagation neural networks (BPNN) (Shao *et al.*, 2015; Tuia *et al.*, 2016).

In addition to the above studies, there are many other studies in which the authors have used local reference measurements to establish a statistical relationship between biomass and remote sensing predictors, where local biomass measurements are predicted with allometric models based on other variables such as tree diameter and tree height not measured directly (e.g. Zianis *et al*, 2005; Fassnacht, 2014).

The other approach to AGB estimation using SAR data is to use coherence and phase (Koch, 2010). Researchers have used the stereo-radargrammetry and allometry capability of TerraSAR-X and TanDEMSAR-X data for forest characterisation and AGB estimation (Karila *et al.*, 2015; Solberg *et al.*, 2015).

In the stereo-radargrammetry techniques, DSMs are derived from dual pairs of TerraSAR-X imagery. The ground level (from airborne lidar or DEM) is then subtracted from the surface level to obtain canopy height models that are analysed and linked through regression analysis to the forest variables of AGB and tree height.

Another method is to use interferometric information (i.e. repeat-pass interferommetry), in which information on the phase similarity (coherence) of two surveys from different points in time can be altered as a result of small changes in geometry (especially in the X-band) (Breidenbach *et al.*, 2010).

Typical research is carried out over large areas (Gaveau *et al.*, 2003) of boreal forest and demonstrates that in winter conditions C- and L-band backscatter intensity are sensitive to changes in woody biomass (biomass of the wooden parts of plants).

A final approach, coherence imagery, uses full polarimetry SAR data and tomography for forest AGB to obtain forest biometrics for the vertical characterisation of forest height and stands (Cloude and Papathanassiou, 2008; Tebaldini and Rocca, 2012; Minh *et al.*, 2016).

3 Fieldwork

Fieldwork was carried out for the collection of on-the-ground data on the size, location, structure and biomass of hedgerows.

3.1 Test Site

Accounting for the availability of satellite imagery, distribution of hedgerows and farm types, and issues around access, an area centred around the town of Fermoy in County Cork, which includes the Teagasc Moorepark Research Centre (see Figure 3.1), was chosen.

This is a highly productive farming landscape, with a rolling lowland physiography dominated by mature, intensive dairy farms with some tillage production. The soils in the area are principally free-draining acid brown earths.

3.2 Pre-visit Target Selection

The test site itself was the footprint of the TerraSAR image set (see section 4.1).

All hedges/scrub in the TSX-SS mode area were digitised from aerial photography (Figure 3.2), except for those around houses and farmyards. A larger area has also been digitised to cover the TSX-SS mode coverage (Figure 3.3).[4] These data were hosted on a geographic information system (GIS) platform on the project intranet to allow for easier collaboration and planning.

The digitised hedges were classified into five classes (Figure 3.4):

1. less than 5 m wide (narrow, no crowns visible) – 157 hedges;
2. greater than 5 m (bushy, crown structure visible) – 181 hedges;
3. treelines (mature trees in a row, no obvious understory) – 23 hedges;
4. outgrown hedges with occasional mature trees – 47 hedges;
5. scrub (patches of trees/bush greater than two trees in width).

The sample has to represent both the range of hedgerow typology in the field site and the range of radar backscatter signals in the radar image. An analysis of radar backscatter by type (see section 5.2) across the field site showed that narrow hedgerows

Figure 3.1. Location of the field site.

4 http://ucc.maps.arcgis.com/apps/webappviewer/index.html?id=b3297776222d40db83cc165f7918b648 (accessed September 2019).

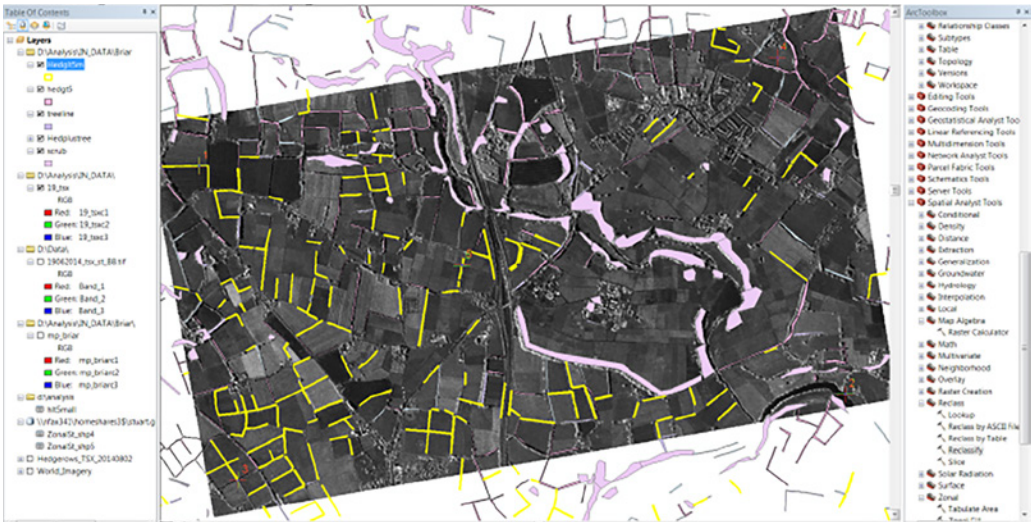


Figure 3.2. Distribution of mapped hedgerows in the target area.

Figure 3.3. Screenshot of the webGIS interface used in data sharing across the project.

Overgrown hedge with trees

Treeline

Wide partially managed

Narrow managed hedge

Figure 3.4. Examples of different hedgerow classes captured in aerial photography.

have a significantly different backscatter profile from those of the other types of hedgerow (Figure 3.5).

A pool of 30 targets/sample plots within the Moorepark area, representing different hedgerows, woodland and scrub types, were selected and visited for biomass assessments (Figure 3.6).

Figure 3.7 shows examples of the different hedgerow types surveyed. Some of the hedgerows comprised raised ditches (banks), which made up a significant proportion of the total hedge volume. The volume of the “ditches” under the hedge was measured so that this could be factored out when developing the SAR biomass regression models.

3.3 In-field Biomass Determination of Sample Plots

3.3.1 Managed and outgrown hedgerows

Plot data, such as hedge and tree measurement, location of plots, were recorded and archived using Field-Map software. A sample distance of 10 m of the hedge lengths was marked from the GPS plot sample point. The diameter and top height of the hedge and the height of the bank below the hedge vegetation were measured at every 1 m interval of the 10 m transect.

Stem and branch diameter, taper (base and top height) and height (hedges > 7 cm diameter of only primary

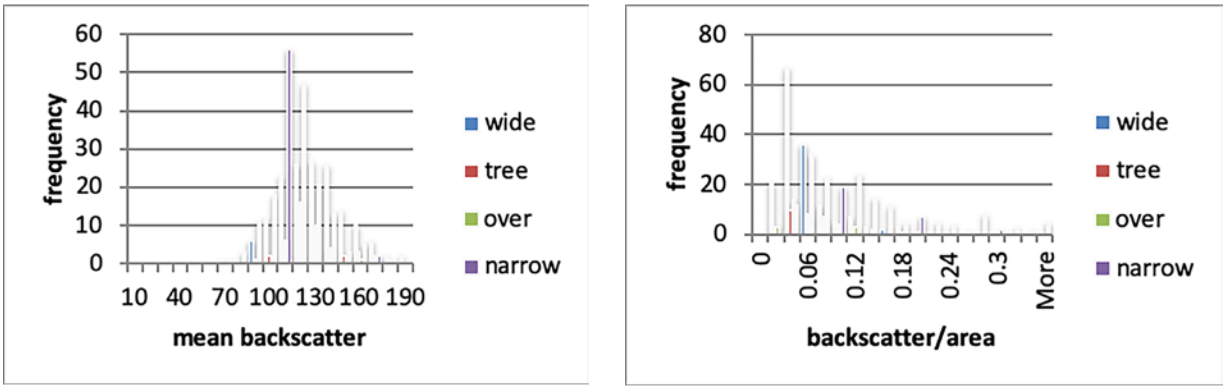


Figure 3.5. Histogram plots of average radar backscatter (left) and backscatter/area (right) for the different hedgerow classes in the trial area.

Figure 3.6. Location of different biomass sample plots in Moorepark, County Cork.

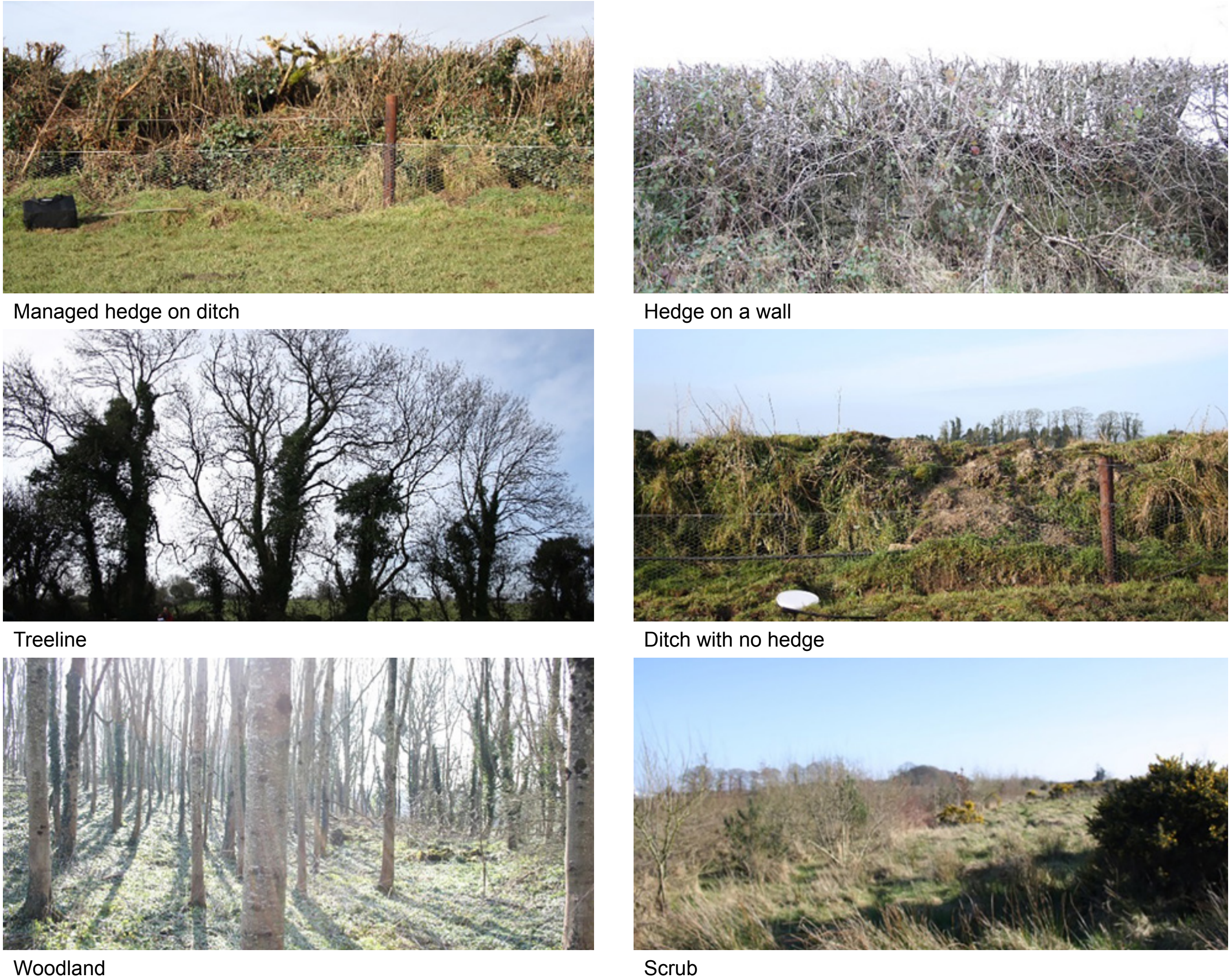


Figure 3.7. Photographs of different vegetation types surveyed.

stems and branches) were collected within the plot area to calculate hedge wood volume using the sum of the frustum of a cone volume (*V*):

$$V(7cm+) = \sum_{i=1}\left(\frac{\pi}{3}\left[D^2 + Dd + d^2\right]h\right) \tag{3.1}$$

where *D* is the base diameter, *d* is the top diameter and *h* is the height of the stem (*i*). Volume was converted to biomass using the Intergovernmental Panel on Climate Change (IPCC) default wood density value of 0.4 kg/m^3 (O'Brien, 2007).

The biomass of branches of a diameter of less than 7 cm [*B*(7 cm+)] was determined using the point intersect cover method to determine the percentage of vegetation cover in the total plot area. The point intersect cover method was carried out on the 10 m plot length at intervals of 0.5 m and at two heights (a quarter and three-quarters of the maximum hedge height). A branch or stem was counted if it intercepted the line at the 0.5 m interval. The percentage cover at a sample height cover is calculated as:

$$cover_h = \sum_{i=1}^{N} 100\frac{P_j}{N} \tag{3.2}$$

where *P* is the number of stem or branch intercepts at sample point *j*, *N* is the total number of intercepts on the 10 m transect (i.e. *N* = 20).

Once the percentage cover of branches of less than 7 cm in diameter was estimated, the AGB [*B*(< 7 cm)] was estimated using a published (Black *et al.*, 2014) generalised equation for scrub species:

$$B(<7cm) = 2.352 + 0.111cover_h \tag{3.3}$$

Individual trees (i.e. uncut trees within the hedge) were assessed for AGB [B(tree)] based on direct DBH (1.3 m) and previously developed algorithms (Black *et* *al.*, 2014). The total biomass (TB) of a plot was then determined as:

$$\text{TB} = B\left(7cm+\right) + B\left(<7cm\right) + B\left(tree\right) \qquad (3.4)$$

3.3.2 New unmanned aerial vehicle method

The drawback of the plot method for measuring hedgerow biomass is that it is very time-consuming. A two-point sampling system was developed for future surveys based on some hedge plot surveys in combination with unmanned aerial vehicle (UAV) surveys. The new proposed method used a combination of UAV estimates of volume and ground-based estimates of biomass. The UAV approach uses photogrammetric and GIS methods to determine the projected 3D volume of treelines and hedges. Biomass was first determined using the plot method approach (outlined above).

The UAV system is a commercially available drone (DR3 solo) but it has been modified to facilitate vegetation surveys using both red, green and blue (RGB) spectral wavelength cameras, has a modified antennae system (for a longer controlled flight range) and uses flight plan software (mission planner) to facilitate accurate geo-reference grid survey flights.

Post processing of aerial photos with an approximate 85% overlap of photos, at a survey height of 90 m above ground level, was used to generate 3D point clouds of the hedgerow sample areas (see Figure 3.6). This is used to generate a canopy DEM or a triangulated irregular networks (TIN) model (Figure 3.8), from which the projected volume (PV) can be derived. All image processing and estimations of PV were carried out using the Pix4Dmapper software (Pix4D, Switzerland).

The PV was then corrected for gaps in the canopy using conventional photographs taken at side angles to the hedgerow (see Figure 3.9, bottom panels). Image analysis (Image R) was used to split the RGB spectra into three different channels and convert the red band to black and white images to determine the side view projected area ratio (SVPAR) according to the following equation:

$$\text{SVPAR} = \frac{\text{silhouette area}}{\text{total side view area}} \qquad (3.5)$$

where the silhouette areas were estimated from the number of black pixels in the side view and the total area is the total number of black and white pixels in the side view.

The final volume of the hedgerow was then derived using the PV and SVPAR, where:

$$\text{V} = \text{PV} \times \text{SVPAR} \qquad (3.6)$$

For individual trees in woodland, circular plots (10 m radius) were established to measure tree diameter. Rectangular plots (10 m length), but with a width varying according to the width of the treeline were established to measure trees within treelines. In all cases, tree diameter at a height of 1.3 m was measured to determine biomass directly using previously developed algorithms

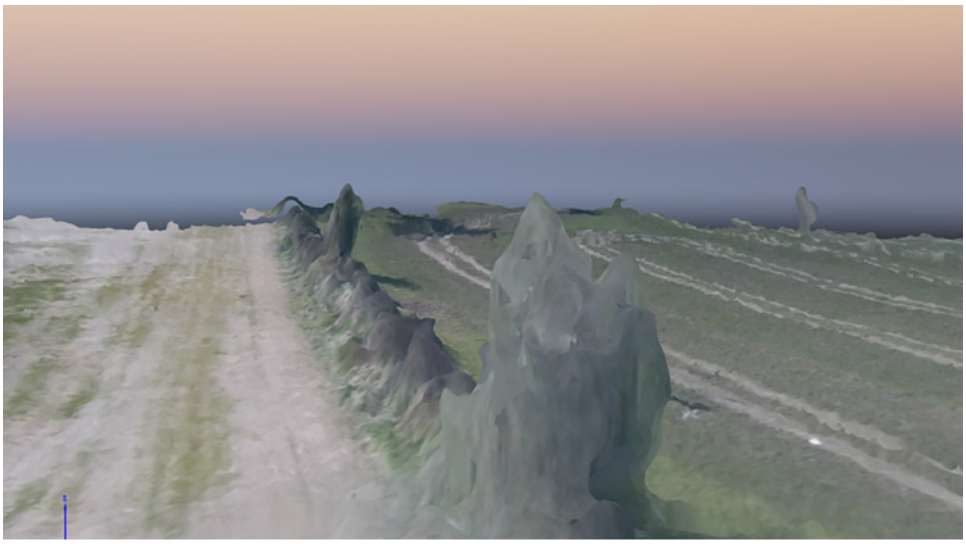


Figure 3.8. A 3D TIN model of a hedge and treeline derived from photogrammetric processing of UAV imagery. The 3D model is used to measure the PV of the hedgerow.

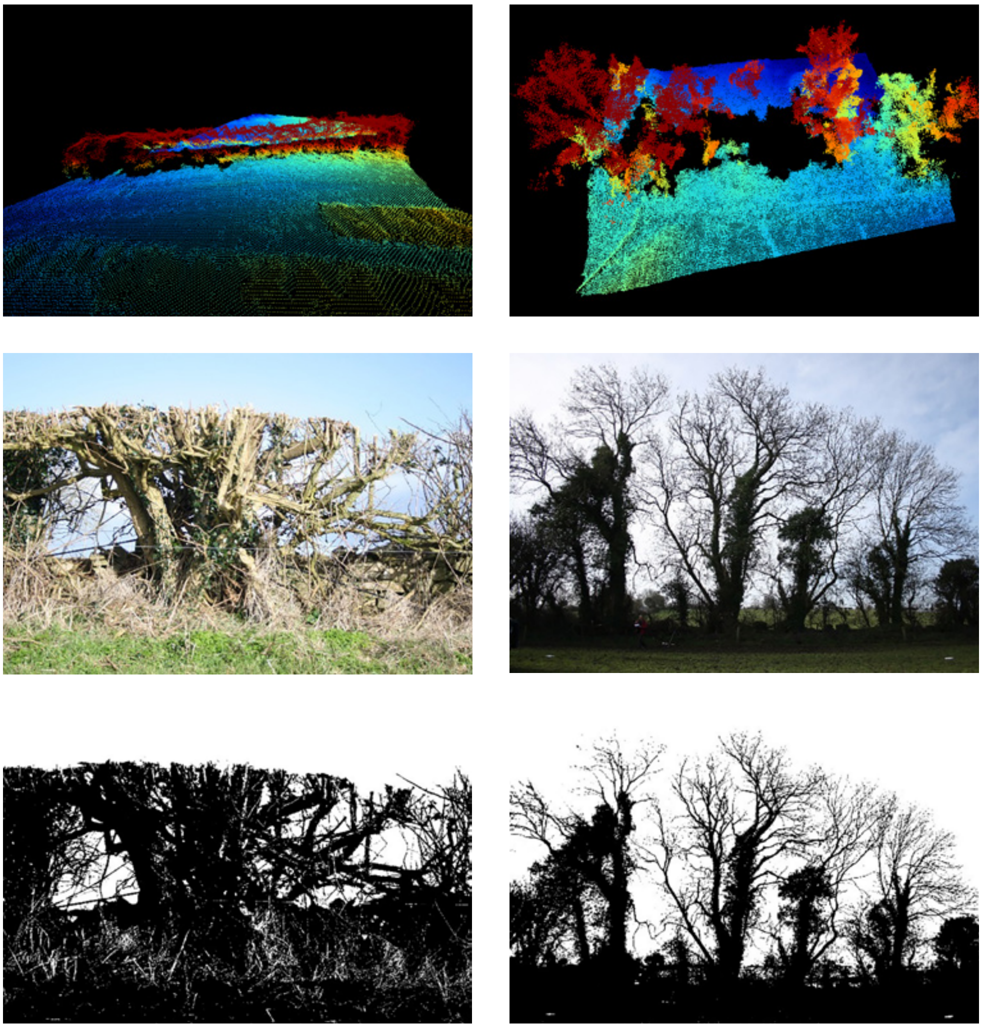


Figure 3.9. An angled view of the 3D point cloud obtained using the UAV and photogrammetric methods. The images on the left are of a managed hedgerow (top, a point cloud; middle, RGB image; bottom, SVPAR image). On the right are the same types of images for an unmanaged hedgerow.

(Black *et al.*, 2014). UAV surveys were also carried out on treelines, but not on woodland plots.

For the shrub layer, circular plots (10 m radius) were established and four line transects were marked out from the centre of the plot in the north, east, south and west directions. Tree diameters (at 1.3 m) were measured for all trees with a diameter of > 7 cm within the plot and biomass was determined using biomass algorithms (Black *et al.*, 2014).

The biomass of trees with a diameter of less than 7 cm and all scrubs was assessed using the line intersect method based on the four transect lines within the plot. Biomass was determined as outlined in equations 3.2 and 3.3 above.

3.4 Field Results

Preliminary analysis of the ground-based biomass assessment and UAV-based volume shows a good relationship, suitable for regression modelling (Figure 3.10). The slope of the regression equation is indicative of hedgerow wood density. The value for the slope in this example is slightly lower than the expected density of wood (0.3–0.6 kg/m^3).

However, the slope-based estimate (see Figure 3.10) would include the density of non-woody biomass, other vegetation and unaccounted air spaces, which are not corrected for using the proposed method.

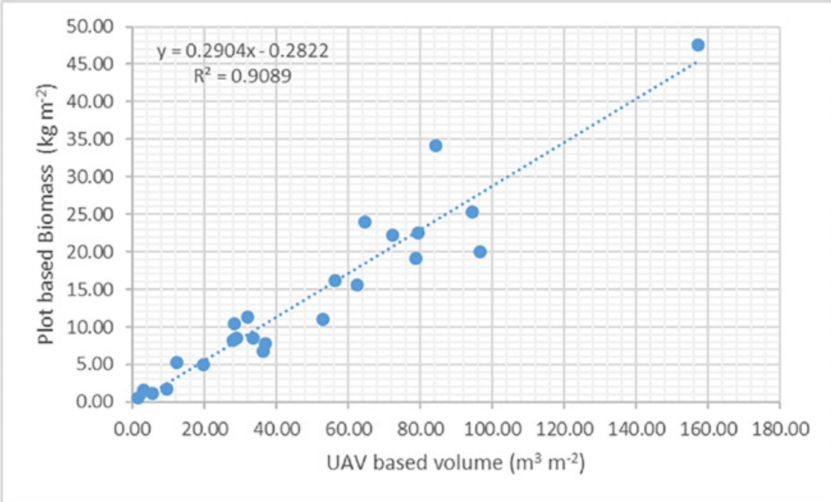


Figure 3.10. The relationship between UAV-derived volume and biomass of different hedgerows and treelines, as derived from plot surveys.

4 Data

4.1 Radar Satellite Data

A time series of VHR TerraSAR-X Spotlight (#8) and Staring Spotlight (#20) mode acquisitions has been acquired over the Fermoy, County Cork study site, covering a 1-year period between 8 June 2014 and 30 June 2015 (Table 4.1).

After review it was decided not to use Sentinel-1 or Advanced Land Observation Satellite (ALOS-2) data, given their lower spatial resolution and longer wavelength, both of which make these instruments sub-optimal for small hedgerow features.

The TerraSAR-X is a commercial German SAR Earth observation satellite owned by Deutsches Zentrum für Luft- und Raumfahrt e.V. The high frequency X-band sensor that it carries can be operated in a number of ways, and for this project we were able to access data through a European Space Agency open access call in two modes: StripMode and Staring Spotlight (Table 4.2).

Staring Spotlight has a longer target illumination time and higher spatial resolution than Stripmap mode, although as a result has a much smaller image footprint and is therefore much more expensive to cover a given area.

The TerraSAR-X Staring Spotlight images were supplied in L1A Single Look Complex format and were processed though the steps below to give the backscatter (σ0):

- co-registered;
- multi-looked;
- speckle filtered using a 5 × 5 window-size Frost filter;
- radiometrically and geometrically calibrated.

All datasets were geocoded to the Irish Transverse Mercator projection (see Figure 4.1 for an example).

The pairs were examined for possible interferommetry analysis; however, because of a number of factors relating to the length of the temporal baseline between pairs, resolution and target size decoherence is too great for interferommetry to be successful with this product (Ali *et al.*, 2017).

Table 4.1. List of datasets acquired by project

Sensor	Date	Off-nadir angle	Mode	Polarisation	Pass/orbit
TerraSAR-X	13/6/2014, 22/6/2014, 28/7/2014, 8/8/2014, 21/9/2014, 22/2/2015, 10/3/2015, 8/4/2015		Spotlight	HH, VV	56, 71
	8/6/2014, 19/6/2014, 2/7/2014, 11/7/2014, 22/7/2014, 2/8/2014, 8/8/2014, 24/8/2014, 15/9/2014, 13/10/2014, 9/11/2014, 1/6/2015, 16/2/2015, 10/3/2015, 27/3/2015, 12/4/2015, 4/5/2015, 26/5/2015, 1/6/2015, 12/6/2015, 30/6/2015		StripMode	HH	3, 71, 147
RADARSAT-2	23/2/2015, 19/3/2015, 12/4/2015, 06/6/2015, 03/7/2015, 13/7/2015, 26/6/2015, 30/6/2015, 10/7/2015	15.11 to 22.10	Full PLR	HH, HV, VH, VV	Ascending Descending
Spot 6/7	28/04/2014, 08/01/2015, 10/03/2015, 26/04/2015, 19/07/2016, 16/01/2015, 15/01/2016, 12/01/2016, 12/10/2015, 04/09/2013, 06/01/2015, 27/10/2012, 01/06/2016	–30.89 to 29.21	Spectral P		
Pleiades (1A, 1B)	02/12/2014, 13/10/2015	–0.7, 20.68	Spectral P		

H, horizontal; P, panchromatic; PLR, polarchromatic; V, vertical.

4.2 Field Biomass Calculation

Using the methodology outlined in Chapter 3, the field data were converted to biomass estimates for the 36 sample sites in the trial area.

4.2.1 Biomass of hedgerows, woodlands and scrubs

A total of 4 out of the 36 samples plots were either wall fences or banks with no biomass (Table 4.3). In 37% of the sample plots, the bank volume represented 22–95% of the total PV. This was more prevalent in managed hedgerows than for the other hedge or site types, which could explain the particular backscatter response.

Scrubland plots had the lowest biomass stock of all of the plot types (see Table 4.3). Woodlands that are not defined as forest (i.e. they do not meet the forest definition, e.g. area of less than 0.1 ha) and treelines have the highest biomass stock (see Table 4.3). Although treelines had a higher biomass stock than woodland, this is largely because treeline sample plots comprised many mature trees. In contrast, all of the woodland plots included tress that were all less than 20 years old.

Managed hedges had a lower biomass than outgrown hedges, as expected (Table 4.4). The coefficient of variation for biomass samples from managed hedges was very high (0.94) because one of the sampled hedges contained mature trees.

Table 4.2. TerraSAR-X product characteristics

Imaging mode	Standard scene size (km)	Resolution (m²)
Staring Spotlight	4 x 3.7	0.25
Stripmode	30 x 50	3.5

Figure 4.1. Example of a TSX-SS mode acquisition (26 April 2014).

Table 4.3. Summary biomass statistics of different hedge and woody biomass habitats in Moorepark

Hedge type	Biomass (kg/m²)	
	Mean	Standard deviation
Managed hedge	5.56	5.28
Outgrown hedge	9.90	1.47
Scrub	0.11	0.03
Treeline	24.82	10.60
Woodland	14.46	3.62

Table 4.4. Derived biomass and computed volume values for different hedgerow types located at the selected sample plots

Plot ID	Type	Plot area (m^2)	Biomass (kg/m^2)	Volume[a] (m^3/m^2)	Bank volume (m^3)	Species
37	Scrub	312.45	0.08			*Salix* spp., gorse,
32	Scrub	312.45	0.14			*Salix* spp., gorse,
33	Scrub	312.45	0.11			Bramble, *Salix* spp., oak, ash
36	Woodland	312.45	10.40			Oak
34	Woodland	312.45	17.36			Ash
35	Woodland	312.45	15.61	62.35		Ash
10	Treeline	312.45	11.36	32.10		Ash
9	Treeline	624.29	25.38	94.51		Oak, ash
0	Treeline	67.26	22.23	72.30		Ash, whitethorn
1	Treeline	266.26	22.55	79.35		Ash, whitethorn
7	Treeline	585.16	24.05	64.52		Ash, oak
13	Treeline	222.36	16.13	56.33		Ash
14	Treeline	295.47	47.60	157.40		Ash, whitethorn
27	Managed hedge	30.45	0.61	1.64	34.15	Ash, whitethorn
26	Bank	11.97			27.30	Grasses
24	Managed hedge	20.76	8.57	33.64	21.57	Ash, whitethorn
25	Managed hedge	19.43	6.81	36.40	14.45	Ash
28	Managed hedge	22.16	1.68	9.65	32.06	Ash, gorse
18	Managed hedge	21.78	1.19	5.41	12.58	Hawthorn
2	Managed hedge	11.25	7.85	36.90	13.08	Ash, whitethorn
3	Managed hedge	15.13	8.53	29.07	10.97	Ash, whitethorn
19	Managed hedge	14.20	5.24	12.30	9.87	Ash, hawthorn, *Salix* spp.
20	Managed hedge	14.39	4.92	19.70		Ash, hawthorn
17	Managed hedge	9.41	1.54	3.20	16.62	Hawthorn
16	Managed hedge	8.05	0.67		17.67	Hawthorn
15	Fence	10.17	0.03			Bramble
21	Fence	11.47				No vegetation
22	Wall	14.24				No vegetation
23	Wall	10.49				No vegetation
5	Treeline	1004.71	34.13	84.20		Ash, beech, oak
6	Treeline	1028.79	19.96	96.78		Ash, beech, oak
11	Outgrown hedge	212.04	11.08	52.90	15.40	Ash, hawthorn
8	Outgrown hedge	106.14	10.38	28.40		Ash, oak, hawthorn
12	Managed hedge with trees	332.55	19.10	78.90	120.00	Ash
29	Outgrown hedge	121.55	8.25	28.07	15.00	Ash, hawthorn

[a]The biomass volume was derived from the UAV survey, but is derived as the total volume minus the bank volume.

5 Remote Sensing of Hedgerow Biomass

5.1 Initial Assessment

After processing the characteristics of hedgerows, as presented in the TSX-SS, the imagery was analysed.

The literature suggests that images acquired during dry periods are more sensitive to the ground surface for backscattering, especially for biomass retrieval, than images acquired in wetter periods. The backscattering is scattered not only from tree and vegetation structures, but also from vegetation water content, soil moisture and sub-canopy roughness. In particular, soil moisture can have a significant effect on backscattering.

We investigated the TSX-SS data from August and September 2014 and February, April, May, June and July 2015 and compared it with weather station data from the test site (daily rainfall on the date of acquisition and 3 days before). June 2015 was the driest period and February 2015 the wettest period.

The issues of seasonality and backscatter return were also addressed by looking at cross-sectional returns across boundary types, and there was no significant difference for different types or across months. This showed that between February and November there was no significant large-scale change for hedgerows and walls over the season, with maximum returns at the boundary being the same, indicating that the bulk of the return is from the woody structure and not the leaves. The main variation in return was a function of the dimensions of the boundary, not the time of year (see Figures 5.1 and 5.2 for examples).

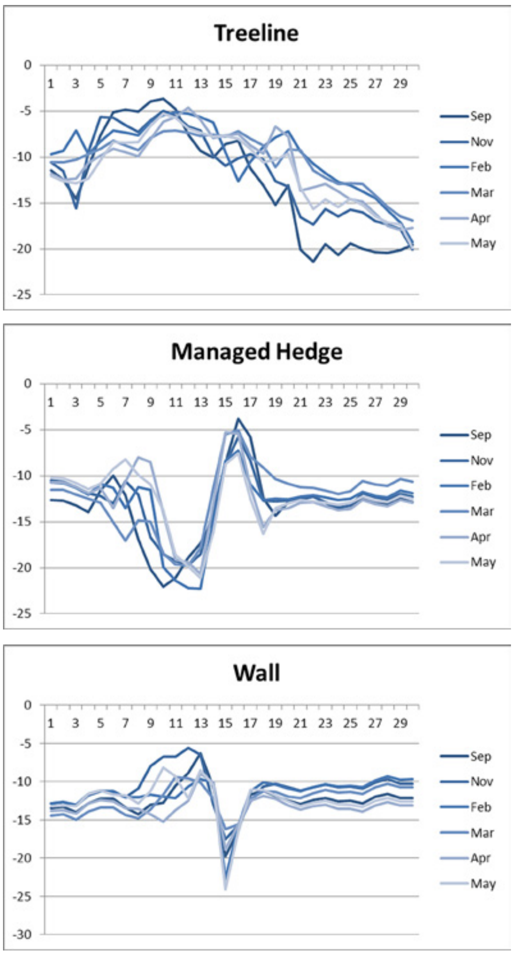


Figure 5.1. Cross-section of the backscatter return for three types of boundary at different months in the year (boundary is located at the 15 m mark).

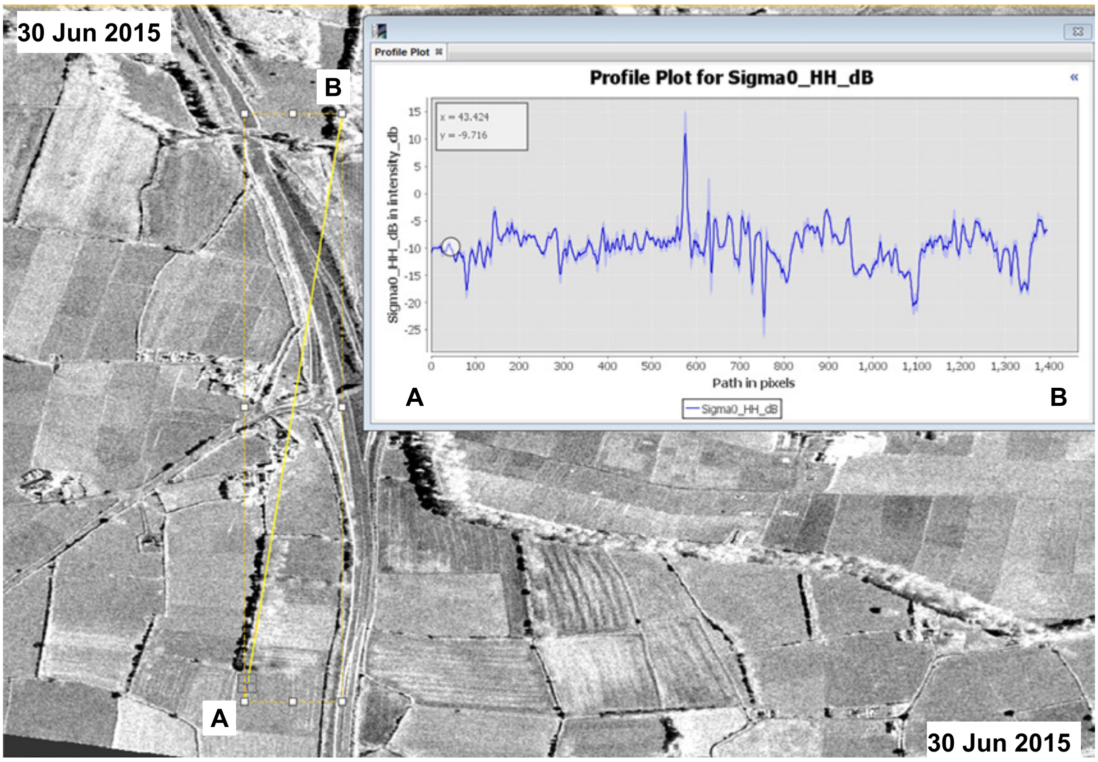


Figure 5.2. The profile plot (north–south, direction) of land cover types and HH-intensity (σ0-dB) image of TSX-SS data.

Examining the characteristic returns of the products used (see Figure 5.2 for an example), we tested different processing algorithms and indexes, such as alpha, lambda, anisotropy, span, ShE, band combination and divergence index.

The sample plots were overlain onto the imagery and the backscatter distribution across the hedgerow/border types was examined (see Figures 5.3 and 5.4).

The ranges of backscatter response are broad, with a similar distribution for the types shown in February and June.

5.2 Analysis

The images were further processed using a variety of filters and indexes such as alpha, lambda, anisotropy, span, ShE, band combination and divergence index.

The ShE and Speckle divergence index filter could best highlight the hedges but could not characterise the hedges as objects distinct from other targets, such as buildings, as they both have double backscatter scattering. Although the Spotlight mode can detect the hedges, there are a lot of mixed pixels (where the pixel images more than one type of surface) because hedges in Ireland are very narrow and are a mix of types, such as managed hedge by fence, wall and sub-base, such as stones and other materials. Therefore, Spotlight, with its 2–3 m resolution in dual mode polarisation, cannot distinguish between these hedge and non-hedge boundaries, and some hedges are too narrow to be detected at all.

Tests of backscatter models against field data proved unsuccessful, with the best responses obtained using a ShE filter in the February image, with a r^2 of 0.302 ($n = 35$) (Figure 5.5 and Table 5.1). There was no relationship found for the June imagery.

5.3 Mapping Hedgerows with Optical Satellites

As noted in section 2.1, image segmentation has been used to detect hedgerows. The Trimble eCognition software is the most extensively used software for extracting linear hedgerow cover from high-resolution images, by adjusting the parameters such as object size, colour homogeneity, shape, smoothness and compactness using the object extraction methods.

The advantage of the OO approach is that it offers new possibilities for image analysis because image objects

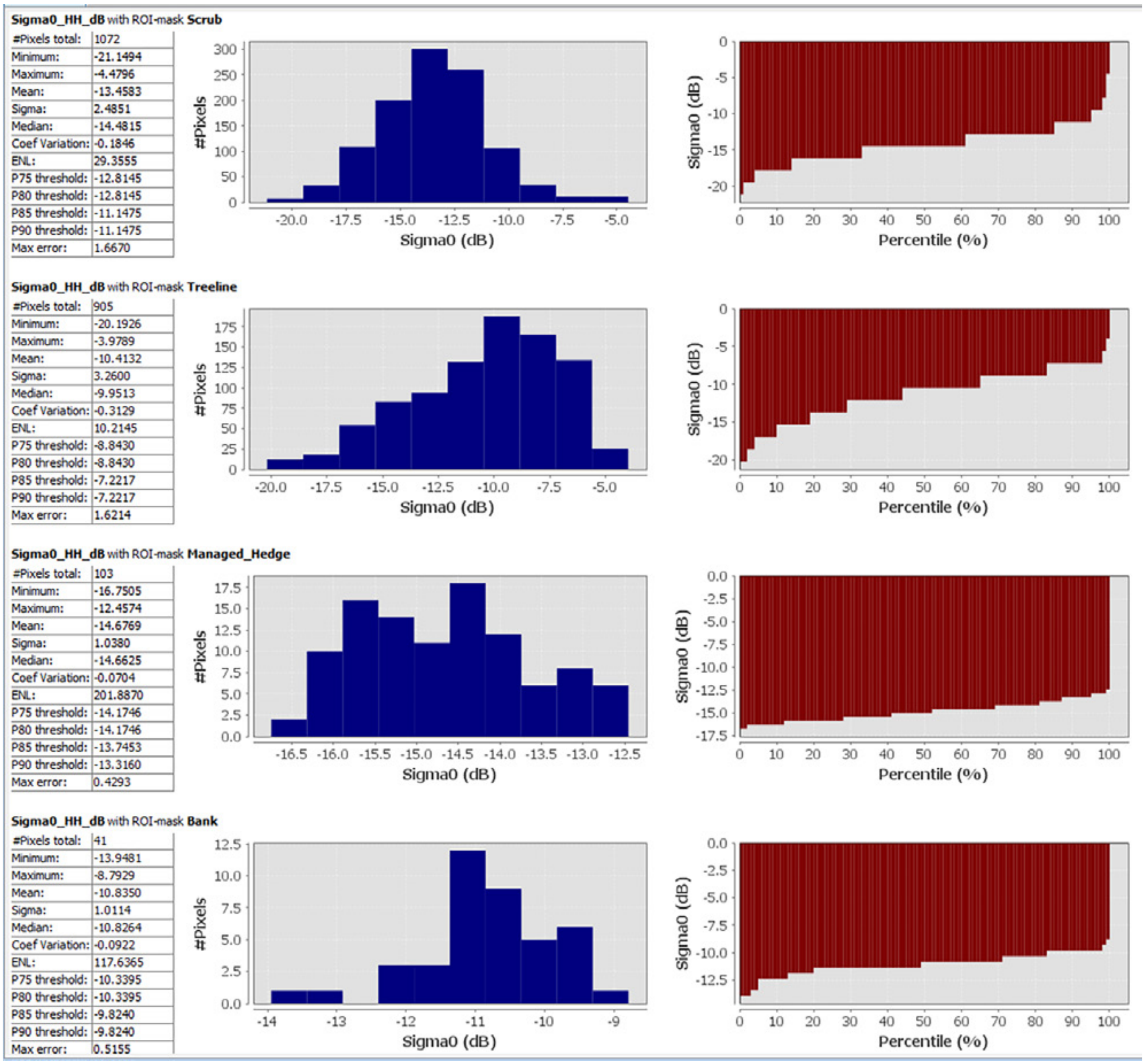


Figure 5.3. Statistical analysis of TSX-SS-data-HH (σ0-dB-16 Feb, 2015), with four field surveying plots of biomass measurement in the Fermoy test site.

can be characterised by features of different origins incorporating spectral values, texture, shape, context relationships and thematic or continuous information supplied by ancillary data. With the integration of additional knowledge it is possible to distinguish ecologically meaningful land covers, such as high nature value or primary habitats.

Objects that do not necessarily have very distinct spectral features may be separated based on other object elements of image characteristics. Moreover, integration of existing vector databases can be achieved during all steps of the classification process, with automation by machine learning methods.

When segmentation approaches were applied in the test area on the Pleidies imagery, classification of hedgerow objects was poor, so Prime2 (Prime2, 2014) boundaries were used to identify potential objects as hedgerows (Figures 5.6 and 5.7)

In keeping with the literature outlined in Chapter 2, segmentation of the Pleiades imagery successfully identified parts of hedgerows while separating out the shadowed component, thus rendering the attempt at estimates of hedgerow area unsuccessful. The effect is particularly evident in winter imagery (shown in Figure 5.8).

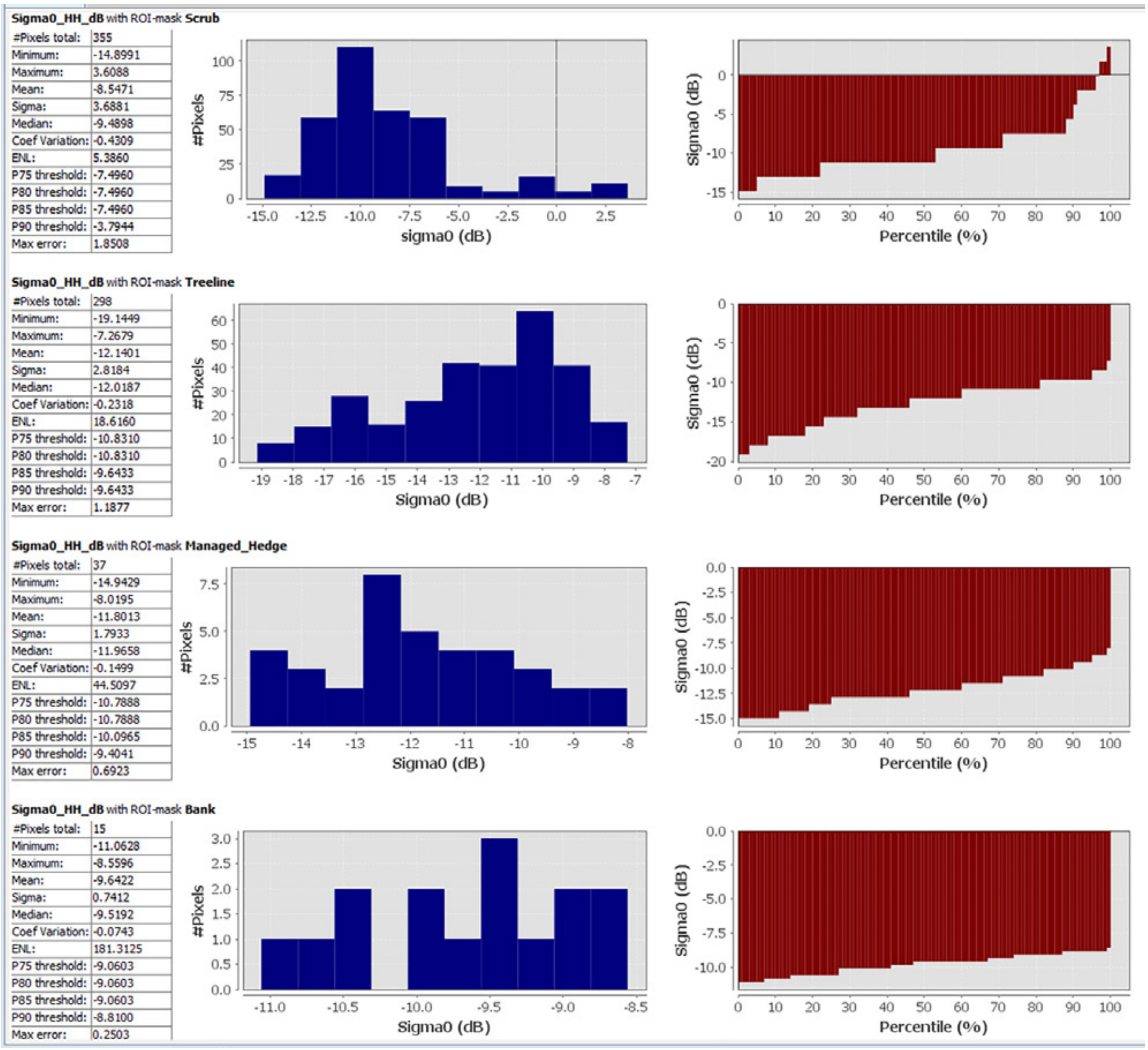


Figure 5.4. Statistical analysis of TSX-SS-data-HH (σ0-dB-30 Jun, 2015), with four field surveying plots of biomass measurement in the Fermoy test site.

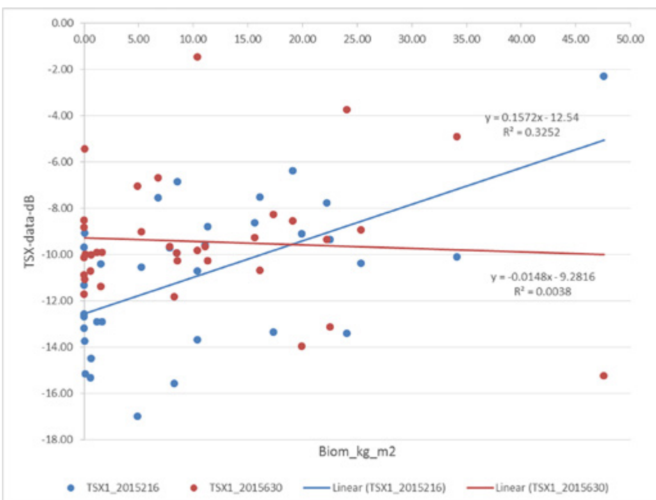


Figure 5.5. Relationship between TSX-SS return and biomass for the 35 field sites.

Table 5.1. Field plot data with TSX-SS backscatter for the two acquisition dates

Plot ID	Biom_kg_m2	Type	Bank_volm3	TSX1_2015216	TSX1_2015630
37	0.084	Scrub	0.000	–9.089	–11.075
32	0.143	Scrub	0.000	–15.171	–10.001
33	0.110	Scrub	0.000	–13.738	–5.424
36	10.403	Woodland	0.000	–10.708	–1.470
34	17.356	Woodland	0.000	–13.357	–8.279
35	15.615	Woodland	0.000	–8.634	–9.262
10	11.362	Treeline	0.000	–8.790	–10.265
9	25.379	Treeline	0.000	–10.394	–8.939
0	22.225	Treeline	0.000	–7.769	–9.349
1	22.551	Treeline	0.000	–9.343	–13.121
7	24.053	Treeline	0.000	–13.417	–3.730
13	16.132	Treeline	0.000	–7.525	–10.682
14	47.602	Treeline	0.000	–2.291	–15.249
27	0.613	Managed hedge	34.150	–15.317	–10.709
26	0.000	Bank	27.300	–11.326	–8.824
24	8.568	Managed hedge	21.571	–6.853	–10.265
25	6.812	Managed hedge	14.454	–7.535	–6.674
28	1.675	Managed hedge	32.060	–12.910	–9.900
18	1.193	Managed hedge	12.580	–12.910	–9.900
2	7.845	Managed hedge	13.080	–9.711	–9.671
3	8.528	Managed hedge	10.974	–9.928	–9.929
19	5.241	Managed hedge	0.000	–10.535	–9.008
20	4.921	Managed hedge	0.000	–16.998	–7.055
17	1.539	Managed hedge	16.623	–10.419	–11.391
16	0.669	Managed hedge	17.670	–14.507	–10.013
15	0.033	Fence	0.000	–13.182	–10.891
21	0.000	Fence	0.000	–12.697	–8.534
22	0.000	Wall	0.000	–12.576	–10.140
23	0.000	Wall	0.000	–9.692	–11.730
5	34.127	Treeline	0.000	–10.094	–4.915
6	19.960	Treeline	0.000	–9.094	–13.966
11	11.080	Outgrown hedge	15.400	–9.569	–9.668
8	10.380	Outgrown hedge	0.000	–13.688	–9.819
12	19.100	Managed hedge with trees	120.000	–6.373	–8.543
29	8.250	Outgrown hedge	15.000	–15.589	–11.826

5.4 Geometric Approach

A re-examination of the field data shows a strong empirical link between hedgerow dimension and estimated biomass, as one would expect (Figure 5.9).

As the biomass saturation resolution issue seemed to be insurmountable, it was decided to try to exploit the backscatter signal in a new way, by looking at its shape. The relationship between biomass and hedgerow dimensions (width and/or height) is strong and the relationship between backscatter cross-section and hedgerow dimension is strong.

Because Illumination/shadow is the result of a fixed geometry between target and satellite (and does not change like shadow due to sun angle) the profile across the target is directly related to the structure of hedgerow irrespective of saturation in the response.

In order to address the geometric effects, etc., identified in section 5.2, a purely geometric approach

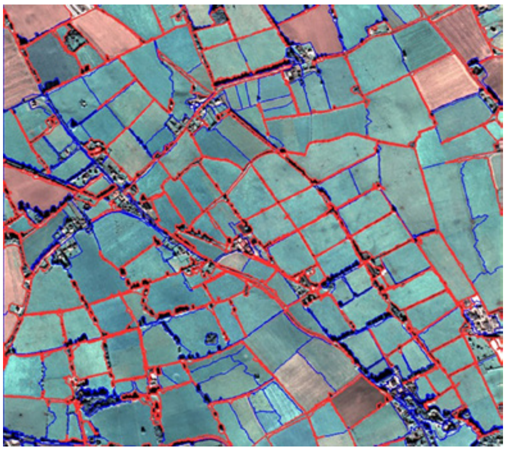


Figure 5.6. Pan-sharpened image of Fermoy town (County Cork) acquired by the satellite Pleiades-1A on 13 October 2015. Images were segmented using the basic segmentation. The red lines are boundaries from the Prime2 dataset; the blue lines are extra boundaries identified in the segmentation process.

Figure 5.7. More complex landscape using the satellite Pleiades-1A image acquired on 13 October 2015 from Moorepark (County Cork). In the segmented image the thick blue polygon lines in the image are hedgerows, but the segmentation also considered the treelines.

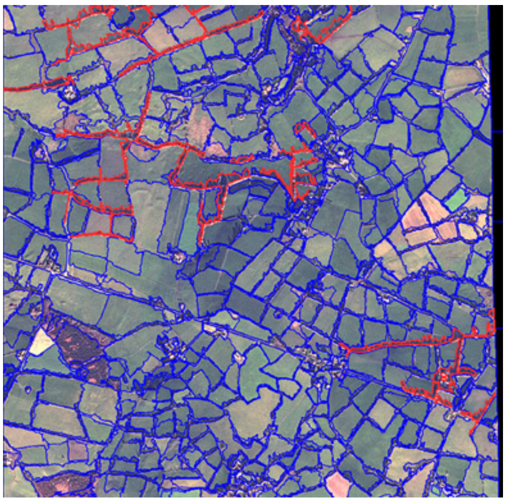


Figure 5.8. Image from the lowlands of Comeragh region (County Waterford) acquired on 23 November 2014. The spatial resolution of this image is 1.5 m, with four bands, including a near-infrared band. The image was captured with a high off-nadir angle of 23 and sun elevation.

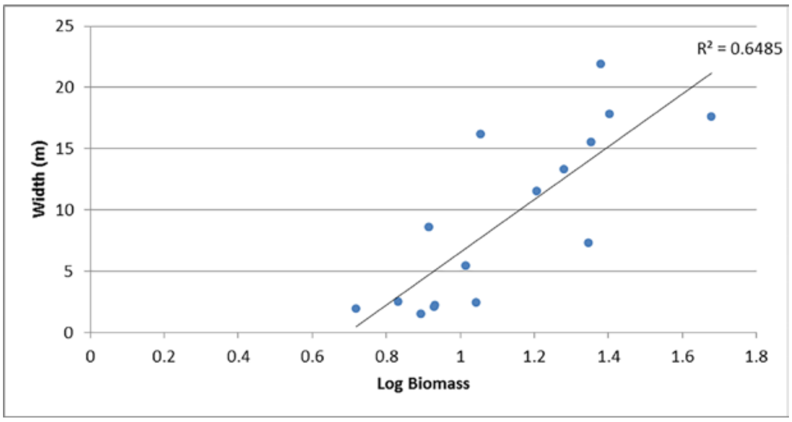


Figure 5.9. Relationship between field-measured hedgerow width and estimated biomass.

has been used for hedgerow detection. Using Prime2 (Prime2, 2014) to identify likely hedgerows, we can use the shape of the backscatter function across hedgerows to detect their presence and to measure their extent.

The field boundary database is processed using a python script to create 20 m-long transects at the midpoint of the boundary line (the red "ticks" in Figure 5.10) using the following method:

1. convert Prime2 vegetation polygons to polylines;
2. simplify the number of plotline vertices;
3. calculate centre points of each polyline and create points perpendicular to the line at the midpoint offset by 10 m either side of the line;
4. join each offset pair of points together as a new polyline to create a 20 m transect line across the midpoint of each boundary;
5. three-dimensional stack profile tool then extracts pixel values across the transect (30 pixels) from the TSX-SS HH image stack along with the orientation of the tick mark.

The corresponding hedgerow widths are measured from the aerial photography.

The algorithm makes use of the height/layover response to objects in the landscape – if using a single orbit (147 SS mode) then the geometry is fixed. The response of backscatter to a hedgerow is illustrated in Figure 5.11.

A number of models have been fitted to a variety of sinusoidal functions. The period of the sine function (Figure 5.12) extracted from the backscatter transect is strongly related to the width of the hedgerow for hedgerow/treelines that are < 20 m wide (Figure 5.13).

However, the strength of the relationship, shown in Figure 5.13, is partly a function of hedgerow orientation to the radar sensor. The relationship breaks down as hedgerows align parallel to the look direction of the sensor, i.e. if there is no shadow, the method fails.

5.5 Discussion

The lack of relationship between radar backscatter response and hedgerow biomass is probably caused by three factors

1. saturation;
2. orientation;
3. structure.

As noted in section 3.2, X-band radar saturates at relatively low levels of biomass density: < 25 t/ha (Table 2.1) or 2.5 kg/m². This is less than the mean value of hedgerow density found in the field survey (6.4 kg/m²). Although there is a suggestion of a relationship in the leaf-off imagery of February, this study confirms the saturation limits of X-band data.

The other significant issue is the relationship between hedge orientation and satellite beam direction or line of sight (LOS) (Figure 5.14).

When the orientation of hedges is parallel to the LOS and they are of sufficient width, backscatter comes from the top of the canopy rather than the stem and sub-canopy scattering.

Figure 5.10. Output of the finalised Prime2 processing, creating simplified field boundary polylines with automatic generation of 20 m transects.

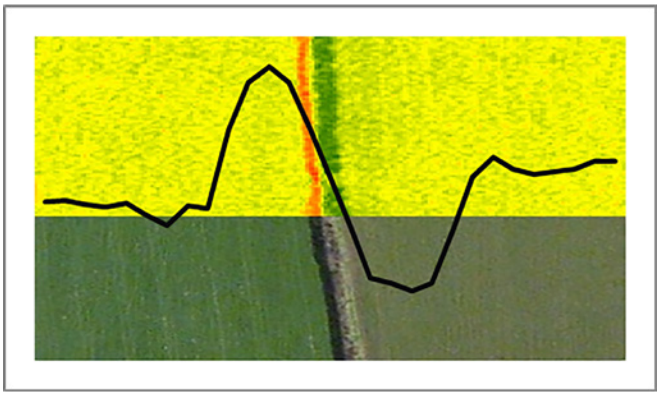


Figure 5.11. Illustration of a backscatter transect across a hedgerow with the TSX-SS image in the top half (red, high backscatter; green, low backscatter).

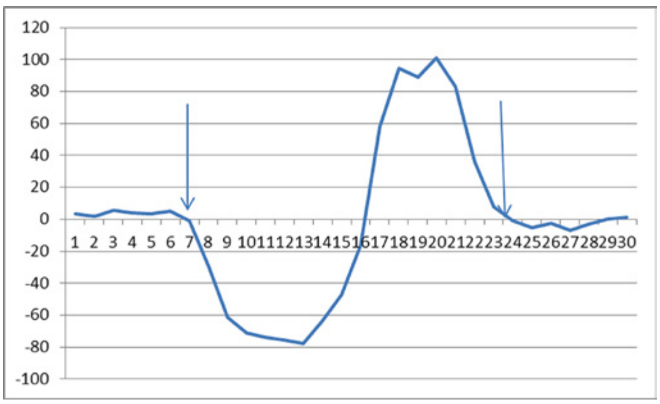


Figure 5.12. Typical cross-section of backscatter; arrows indicate the period of the sine wave measured in metres.

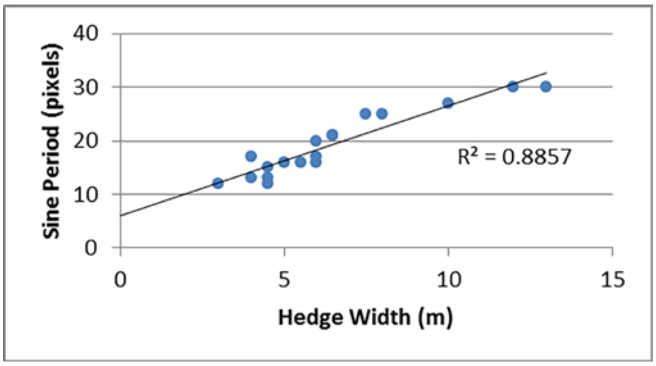


Figure 5.13. Relationship between width of the hedgerow and period of the backscatter sinusoidal profile.

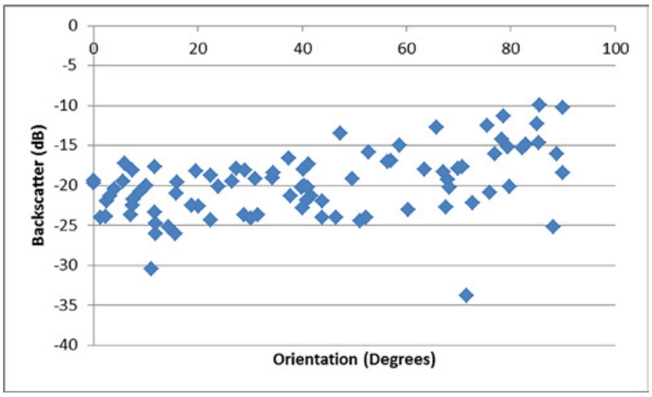


Figure 5.14. Relationship between random hedgerow backscatter response and orientation in degrees.

If the LOS is perpendicular to the hedgerow orientation, it will produce the complex backscattering from the top of the canopy, stem and branches, and also the sub-surface, such as soil moisture and roughness. It is the difference between looking down the length of the hedgerow and seeing only the top, and looking at the side elevation of the hedgerow and seeing the whole structure.

The lack of a full range of polarisation data in our TSX-SS database is also another limitation because HV/VH is more sensitive to trees and vertical objects and can help in a backscattering model to distinguish how much backscatter comes from the stem.

The difficulties of complex backscattering analysis in this project were compounded by the complex structure of hedges in the test site and the range of targets that can be characterised as a hedgerow – a narrow hedge, an unmanaged hedge and a treeline behave very differently in their backscatter response, especially as a function of orientation and LOS of SAR sensor. In many hedgerows, when a transmitted wave can penetrate through branches, stem and then to soil, soil moisture, soil roughness and sub-base material become far more dominant in influencing backscatter than in a forest.

The result has shown HH/VV polarisation mode is not sensitive to the structure and biomass range of hedgerows.

5.6 Conclusion

Statistical analysis and regression modelling for biomass retrieval from TSX-SS intensity has shown low correlation. Backscattering model analysis with the dual mode of TSX data performed poorly.

Retrieving the real biomass using TSX-SS data proved difficult.

TSX-SS/LOS issues are complex with respect to cross-hedge orientation:

- Hedgerows are effectively a solid target for TSX-SS. We cannot distinguish between hedges, ditches and walls using backscatter approaches (or OO approaches).

- The average hedgerow biomass density is beyond the saturation threshold for X-band instruments.
- There is no direct method of estimating biomass from backscatter.
- It is possible to use TSX-SS to estimate the width of some hedges/treelines but only with respect to near-perpendicular hedge/sensor orientation, so allometric estimates are possible but limited.

6 Estimating Annual Change in Hedgerow Stocks

6.1 The National Hedgerow Stock

A figure of 300,000 km of hedgerow in Ireland is often quoted; however, the source of this figure has been impossible to identify. In order to estimate the true length of hedgerow in Ireland, geospatial analysis of the Prime2 map layer was carried out.

By definition, all hedgerows are boundaries, but not all boundaries are hedgerows. In the Prime2 database, all fields in Ireland are delineated as polygon objects, with the boundaries as hedgerows or stonewalls. Fences are generally not captured as boundaries in the Prime2 database as they are not visible on the aerial photography that forms the basis of the mapping. The Prime2 vegetation/field polygons contain no intelligence as to the nature of the boundary. Using the pan-European LUCAS land-use survey transect data it is possible to model the likelihood of a boundary being a stone wall.

6.2 LUCAS Data

An alternative source of data for monitoring the hedgerow population is the pan-European LUCAS survey from the European Economic Area (Gallego and Delincé, 2010).

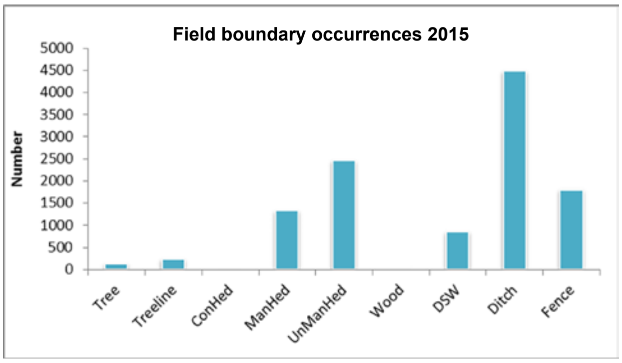
LUCAS records the land use across Ireland on the intersection of 2 × 2 km grids, capturing approximately 3500 point observations. It also carries out transect records at each point, noting the land uses and boundaries on a 250 m transect eastward from each point. The boundaries recorded are tree, treeline, conifer hedge, managed hedge, wood, dry stone wall (DSW), ditch and fence. The points are revisited every 3 years, providing useful information on the number of hedgerows and on management; > 10,000 boundary-type observations are provided. It should be noted that the observations are text strings with no indication of where on the transect a boundary is crossed – in most cases ditches and hedgerows are coincident, essentially forming a single boundary; the same is true for hedgerows and fences.

Histograms on the distribution of these field types are shown in Figure 6.1 for 2012 and 2015. Ditches are the most common feature, followed by hedgerows, both unmanaged and managed, fences and DSWs. The big change between the 2 years is the shift from unmanaged to managed hedgerows in the record.

Mapping the occurrence of hedgerows, unmanaged hedgerows and DSWs shows where DSWs are most common. The maps in Figure 6.2 show how DSWs are concentrated in the karst/limestone regions of the west/mid-west.

Using this distribution of boundary types across the country, the likelihood of a boundary being a DSW and not a hedgerow can be mapped (Figure 6.3).

The Prime2 vegetation polygons (essentially fields and gardens) were overlaid with the LPIS, the national database of farmed land, to identify only farm fields. The polygons were then converted into polylines and a new clean topology created, with all lines separated by less than 1 m eliminated (Figure 5.10 shows examples of this new national boundary line layer).



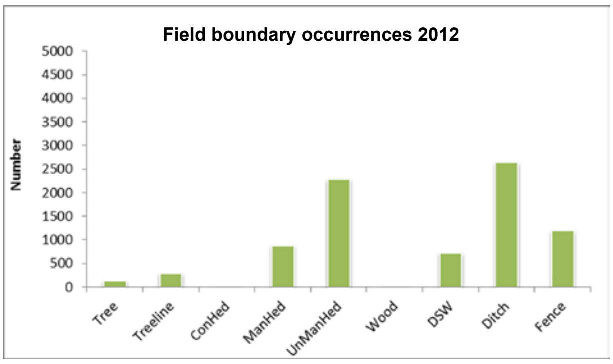


Figure 6.1. Frequency histograms of the boundary types recorded in the 2015 and 2012 LUCAS surveys.

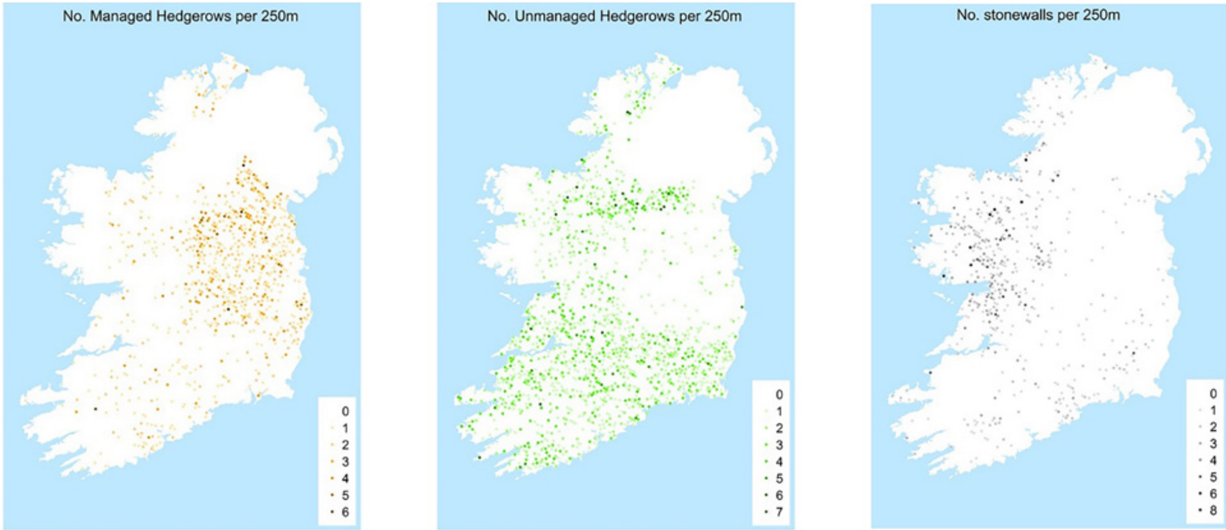


Figure 6.2. Maps showing the occurrence of the types of boundary in the LUCAS 2015 dataset. Managed hedgerows (left), unmanaged hedgerows (middle) and DSWs (right).

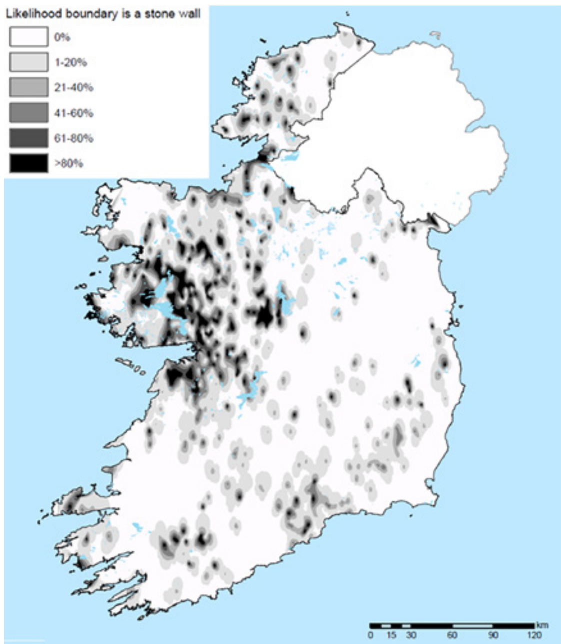


Figure 6.3. Likelihood that a field boundary is a DSW.

Using geo-intelligence from LPIS – parcels clustered into farms – boundary lines were classified as "shared", i.e. a common boundary between farms; "un-shared" (external boundaries not shared with another farm e.g. a road frontage); and "internal" boundaries, i.e. field divisions within a farm.

This was carried out as evidence shows that common boundaries are less likely to be removed or managed and shared hedgerows cannot be included in the GLAS. Estimates of the total length of the different types of hedgerow boundary were created using a weighted sum of boundary lengths with respect to the DSW probability created. The results are shown in Table 6.1 and Figure 6.4, giving a national estimate of 689,000 km for non-DSW boundaries.

Although the total estimate is much bigger than that currently used (300,000 km), this is because the 300,000 km figure is derived from the few county surveys produced (see the following section). The surveys in Cavan, Roscommon, N. Kerry, Sligo,

Table 6.1. County-level estimates of the length of hedgerows

County	Hedgerow length (000 km) (% of total)			
	Total	Unshared	Shared	Internal
Clare	33	19 (58)	5 (15)	9 (27)
Cork	88	50 (57)	13 (15)	25 (28)
Cavan	30	17 (57)	4 (13)	9 (30)
Carlow	10	5 (50)	2 (20)	3 (30)
Dublin	5	3 (60)	1 (20)	1 (20)
Donegal	32	19 (59)	5 (16)	8 (25)
Galway	39	23 (59)	7 (18)	9 (23)
Kildare	16	10 (63)	2 (13)	4 (25)
Kilkenny	26	13 (50)	5 (19)	8 (31)
Kerry	38	23 (61)	6 (16)	10 (26)
Longford	14	8 (57)	2 (14)	4 (29)
Louth	9	6 (67)	2 (22)	2 (22)
Limerick	35	21 (60)	5 (14)	9 (26)
Leitrim	21	11 (52)	3 (14)	7 (33)
Laois	18	11 (61)	3 (17)	4 (22)
Meath	26	16 (62)	4 (15)	6 (23)
Monaghan	22	12 (55)	4 (18)	6 (27)
Mayo	35	22 (63)	5 (14)	7 (20)
Offaly	19	13 (68)	3 (16)	4 (21)
Roscommon	26	15 (58)	4 (15)	6 (23)
Sligo	19	11 (58)	3 (16)	5 (26)
Tipperary	48	27 (56)	8 (17)	13 (27)
Waterford	17	10 (59)	2 (12)	5 (29)
Westmeath	20	13 (65)	3 (15)	4 (20)
Wicklow	14	8 (57)	2 (14)	4 (29)
Wexford	29	16 (55)	5 (17)	7 (24)
Ireland	689	406 (59)	106 (15)	177 (26)

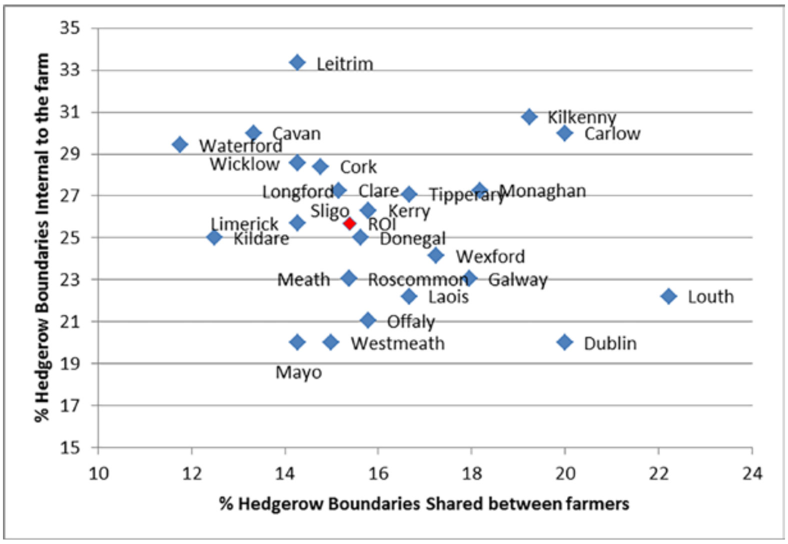


Figure 6.4. Relationship at the county level between the percentage of boundaries shared by farmers and the percentage of boundaries internal to farms.

Donegal and Laois give a typical length of hedgerow of 7 km/km². Using a figure of 70,273 km² as the area of the state, the estimate of km of hedgerow per square km from our study is 9.8 km/km² for the entire country.

However, importantly, the definition of a hedgerow in the county surveys is much narrower than that used in this study – they use a botanical definition that excludes overgrown walls, treelines, forest boundaries, etc. In order to understand the level of potential underestimation for all woody biomass field boundaries when using this stricter definition of hedges, the county survey for Monaghan (Foulkes, 2010) was recreated using our field boundaries.

Figure 6.5a shows one of the field squares from the Monaghan report, in which the hedgerows identified are labelled with red lines. Figure 6.5b shows the boundaries identified in the BRIAR biomass boundary dataset. The difference is quite evident for the reasons given earlier. This is in no way to be construed as a critique of the hedgerow survey or the published hedgerow survey methodology. The current project is looking at all NFWB on farms, not just hedgerows.

The average hedgerow width recorded across all of the completed county hedgerow surveys is 2.7 m. This then gives an estimate of total hedgerow area using a total length of 689,000 km of 186,000 ha or 2.6% of the state.

6.3 Estimates from the County Hedgerow Survey

A number of counties carried out detailed field surveys of hedgerows in the mid-2000s. These all used the same methodology and took 1 km sample grids at the corner point of 10 km grids across the county. Taking County Cavan (Figure 6.6), with its wide range of land uses and land use capacity, as an example, we can compare the grid sample field surveys conducted in 2005 (Gloria Environmental Services, 2006) with the length of hedgerow captured in the same grids in 1995 and 2014 (Figure 6.7 shows an example) using manual inspection of aerial photography.

Manually measuring the length of visible hedgerows from aerial photography over the 19 years for all of the survey squares, there is a net loss, with most of the losses occurring in the period from 1995 to 2005. The total loss over 19 years is 14 km out of a total length of hedgerow of 205 km in the 18 1 km squares, an equivalent net loss of approximately 0.3% of stock length per annum (Table 6.2).

The big difference observationally is the move from unmanaged hedgerows in 1995 to managed hedgerows in 2014, and this is reflected in the analysis of LUCAS points in Figure 6.1. New hedgerows are associated with road and housing developments (although there is usually a net loss associated with these changes depending on the total loss of

Figure 6.5. Example of a survey square from the Monaghan hedgerow survey (left) compared with the boundaries identified in the BRIAR biomass boundary database (right).

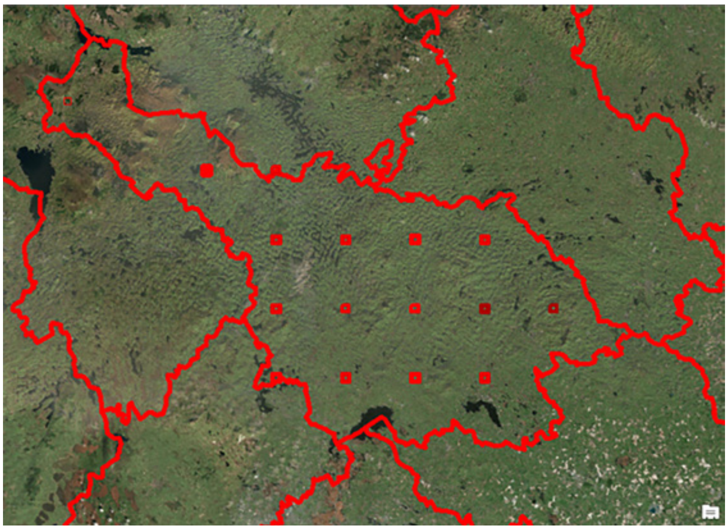


Figure 6.6. Sample km squares in the County Cavan hedgerow survey, 2005.

Figure 6.7. Comparison of one of the County Cavan hedgerow survey grids in 1995 (left) and 2014 (right).

pre-existing hedgerows within a development). Most hedgerow loss is associated with farm restructuring (see Figure 6.7). Hedgerows that become associated with afforestation are not assumed to be lost in this carbon-accounting scenario.

To complement this analysis we also used the aerial photography archive to give us another way to assess net removal rates. We randomly selected 1000 hedgerows, 500 present in 1995 and 500 present in 2015 (Table 6.3).

Of the 500 hedgerows identified in 2015, only 16 were not hedgerows in 1995 (so therefore had been planted after 1995), but, of the 500 hedgerows identified in 1995, 23 were now forest in 2015 and 47 had been removed by 2015. This gives a net decrease of 5.5% in total. If we allow that hedgerows within forests are still present for biomass purposes, then the net removal of hedgerows in the last 20 years equates to 3.2% i.e. 0.16% per annum (see Figure 6.8 for examples).

Table 6.2. Length of hedgerow (km) in each of the County Cavan sample grids from the 2005 field survey

Grid	1995[a]	2005	2014[a]	Change 1995–2005	Change 2005–2014	Change 1995–2014
200330	11.1	11.1	11.1	0.0	0.0	0.0
210320	0.0	0.0	0.0	0.0	0.0	0.0
230290	9.8	9.7	9.4	–0.1	–0.3	–0.4
230300	13.3	9.8	9.8	–3.4	0.0	–3.4
230310	15.0	14.6	14.4	–0.4	–0.2	–0.6
230320	12.3	12.3	12.3	–0.1	0.0	–0.1
240290	17.5	16.1	15.8	–1.4	–0.3	–1.7
240300	12.3	11.5	11.1	–0.7	–0.4	–1.2
240310	11.6	11.9	11.7	0.3	–0.2	0.1
240320	0.0	0.0	0.0	0.0	0.0	0.0
250280	4.9	4.7	4.7	–0.2	0.0	–0.2
250290	13.5	12.1	11.8	–1.4	–0.3	–1.7
250300	15.1	15.0	14.8	–0.1	–0.2	–0.3
250310	13.9	12.7	12.0	–1.2	–0.7	–1.9
260290	10.2	10.2	10.1	0.0	–0.1	–0.1
260300	17.8	17.4	16.7	–0.4	–0.7	–1.1
260310	13.8	13.5	13.0	–0.3	–0.4	–0.7
270300	12.8	12.1	12.1	–0.7	0.0	–0.7
Total	204.6	194.6	190.8	–10.1	–3.8	–13.9

[a]The lengths of hedgerows in 1995 and 2014 are measured from aerial photography.

Table 6.3. Change in status of 1000 hedgerows between 1995 and 2015

Year	Hedge	Not hedge
1995	984	16
2015	930	70

6.3.1 National point cloud

There is now a growing amount of free lidar data of high quality available from the Geological Survey of Ireland on the National Open Topographic Data Viewer.[5] The data are free and are processed to a level sufficient for hedgerows. The data are supplied as DTM and DSM tiles.

By subtracting the DTM from the DSM, a digital canopy model (DCM) is created.

Comparing the DCM hedgerow heights with the recorded field heights (which do not overlap temporally), a good match is found between the maximum height of the hedgerow (Figure 6.9) and the mean height of the hedgerow (Figure 6.10).

The Ordnance Survey Ireland (OSI) have recently proposed a photogrammetrically produced national 25 cm point cloud from aerial photography. This, combined with Prime2 boundaries, can produce data of sufficient quality to reliably estimate the height of a field and the volume of field boundaries.

5 https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5 (accessed September 2019).

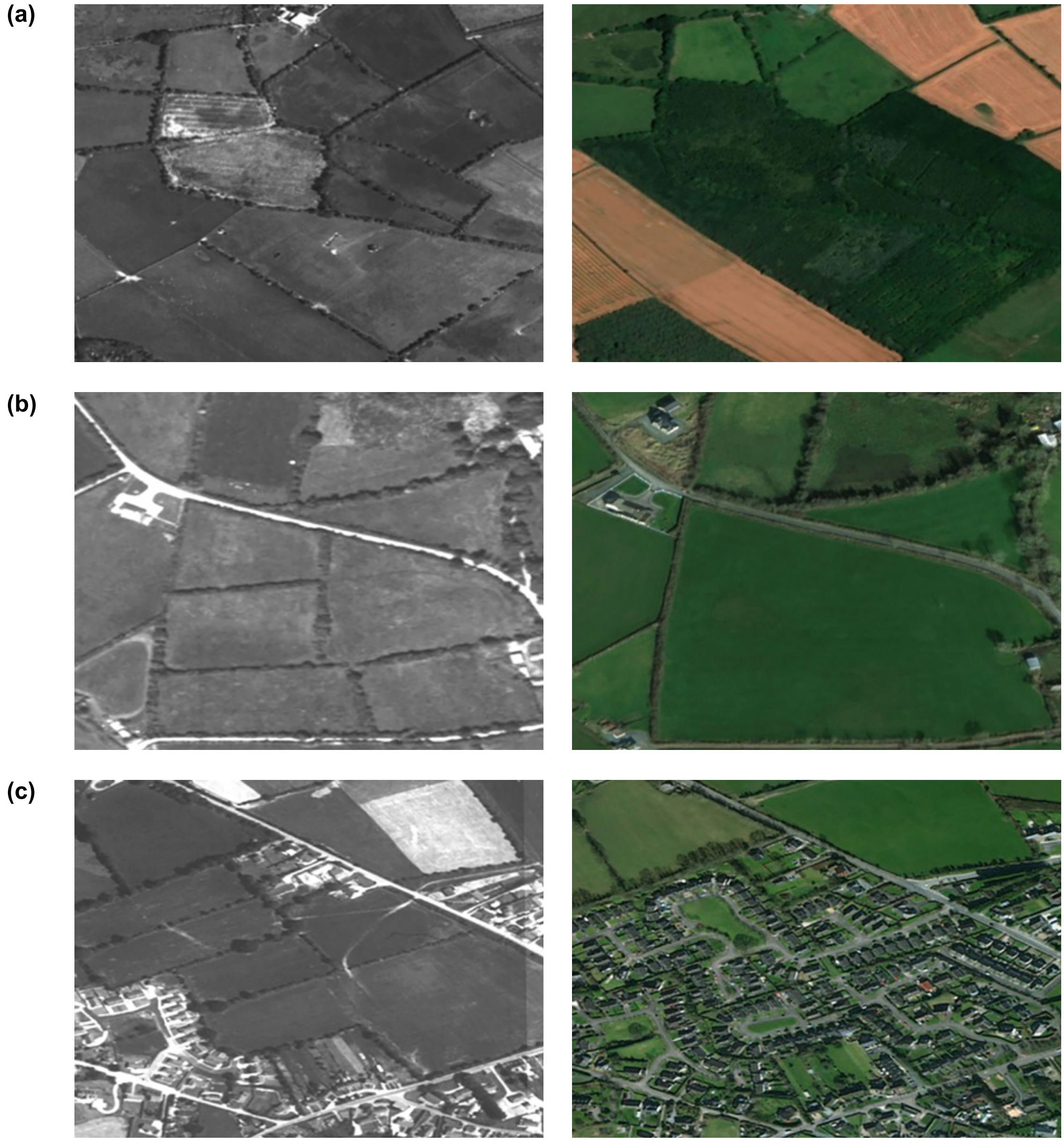


Figure 6.8. (a) Hedgerows consumed by afforestation; although lost as landscape and habitat features they cannot be considered a net biomass removal; (b) hedgerows lost to farm restructuring; (c) hedgerows lost to urban expansion.

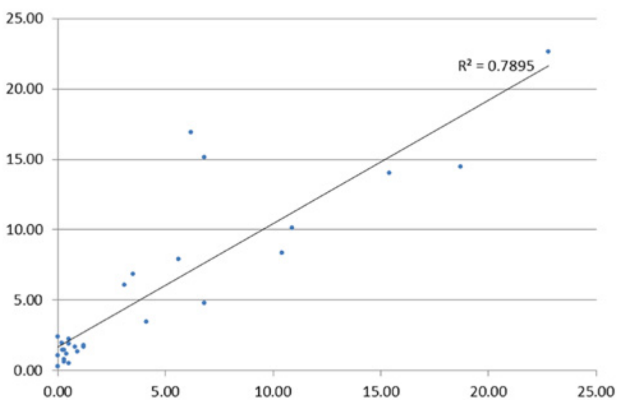


Figure 6.9. Maximum field height of a hedge compared with the maximum height in the DCM.

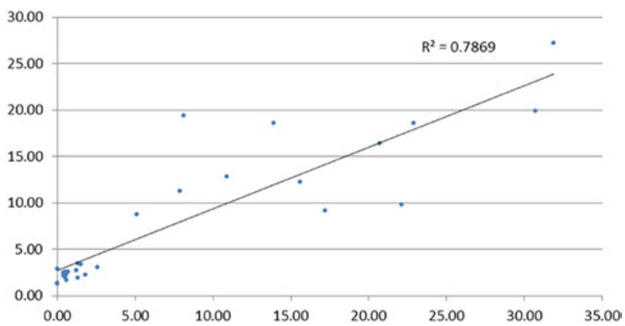


Figure 6.10. Mean field hedge height and mean height in the DCM.

7 Observations and Recommendations

This report demonstrates that radar is an inappropriate technology for characterising hedgerows in the Irish landscape.

The combination of the confounding effects of saturation, geometry, biomass density and structure means that no great confidence can be attached to either direct estimates of biomass or estimates modelled from radar-derived estimates of hedgerow dimensions.

It is clear from this study, along with the literature reviewed and the conclusions of the early hedgerow report (Black *et al.*, 2014), that lidar is the most appropriate technology for national-scale estimates.

The approach to 3D modelling of hedgerows using structure in motion drone-acquired 3D models, introduced in this report for the first time, should be developed, as it has great potential to speed up future hedgerow surveys.

The analysis in the earlier report (Black *et al.*, 2014), the literature and the current study all show the difficulty of separating the hedge from the bank on which it sits. In national-scale analysis this could lead to an overestimate of AGB. However, it is clear that the bank is "man-made" and, for mature hedgerow, is largely hedgerow biomass (root system). The bank contribution to biomass (and thus carbon) should be treated the same as the estimates of AGB (indeed, there is an argument to make that, as a man-made structure, the "bank" itself is above ground, i.e. not part of the ground).

The estimate of hedgerow length nationally, at 689,000 km, is larger than the estimate from the partial hedgerow surveys of seven counties carried out in the last decade. This is attributable to the use of a very wide definition of "hedgerow" in the report compared with the tight ecological definition of hedgerow used in the county surveys.

The estimated net removal rate of between 0.16% and 0.3% per year is significant, suggesting that hundreds of km of hedgerow have been removed a year, compared with the approximately 250–1050 km of hedgerow removal granted permission under the EIA over 6 years.

Taking a mid-range estimate of 0.2% hedgerow removal per annum based on the current stock, this is equivalent to 1378 km, with an average width of 2.7 m, which equates to an area of 372 ha/per annum.

It should be noted that the 1300 km of hedgerow planned to be planted under tranche 1 of GLAS would not be observable in the aerial photography record at the time of planting.

Although the carbon implications of hedgerow removal can be estimated, the sequestration impacts of hedgerow management are entirely unknown. Policy has a big impact on the extent and type of hedgerow management and is creating a binary population of hedgerow, with unmanaged farm boundaries and highly managed internal field divisions.

The recommendations of this report are as follows:

- A national lidar inventory of hedgerows should be commissioned and repeated at 5-yearly intervals.
- The quickest and cheapest approach is to use the OSI proposed 25 cm photogrammetric point cloud (as a lidar proxy) to perform a national 1 km sample survey, in the same way as published county surveys (see Chapter 6). This could be carried out as a 12-month desk study and could be updated as part of the OSI national update cycle.
- Studies on the sequestration difference between managed and unmanaged hedges should be undertaken (including life-cycle studies on the fate of biomass removed during management).
- Field experiments need to be undertaken to measure directly the carbon stock through destructive testing of the biomass in hedgerows.
- Consideration should be given to the carbon stored in the bank (on which the hedgerow is planted).
- Existing radar technology can detect hedgerows but cannot estimate hedgerow AGB.

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Abbreviations

AGB	Above-ground biomass
DAFM	Department of Agriculture, Food and the Marine
DBH	Diameter at breast height
DCM	Digital canopy model
DEM	Digital elevation model
DSM	Digital surface model
DSW	Dry stone wall
DTM	Digital terrain model
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
GAEC	Good agricultural and environmental condition
GIS	Geographic information system
GLAS	Green Low-carbon Agri-environment Scheme
InSAR	Interferometric synthetic aperture radar
LOS	Line of sight
LPIS	Land Parcel Identification System
NFWB	Non-forest woody biomass
OO	Object orientated
OSI	Ordnance Survey Ireland
PV	Projected volume
RGB	Red, green and blue
SAR	Synthetic aperture radar
ShE	Shannon entropy
SMR	Statutory Management Requirements
SVM	Support vector machine
SVPAR	Side view projected area ratio
TIN	Triangulated irregular networks
TSX-SS	TerraSAR-X Staring Spotlight
UAV	Unmanned aerial vehicle
VHR	Very high resolution
VHSR	Very high spatial resolution

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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BRIAR: Biomass Retrieval in Ireland using Active Remote sensing

Authors: Stuart Green, Shafique Martin,
Saeid Gharechelou, Fiona Cawkwell and Kevin Black

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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Hedgerows are a very significant component of the Irish landscape. They perform multiple functions, acting as boundary markers and stock-proofing fencing, supporting bio-diversity and controlling run-off. The purpose of the BRIAR (Biomass Retrieval in Ireland using Active Remote Sensing) research project was to examine the use of active remote sensing tool imaging radar to estimate biomass in hedgerow.

Developing Solutions

High-resolution radar Earth observation data cannot be used to accurately and directly estimate hedgerow biomass because of saturation effects. A new upper limit on the extent of boundary biomass has been established and a new field approach to mapping estimates of hedgerow biomass using drones has also been developed. The study recommends that the national photogrammetric "point cloud" from the Ordnance Survey be used as a basis for a national inventory modelled on existing county field surveys in order to accurately measure hedgerow volume and thus above-ground carbon storage.

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