Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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Carbon Sequestration by Hedgerows in the Irish Landscape

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

Environmental Protection Agency

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EPA Climate Change Research Programme 2007–2013

Carbon Sequestration by Hedgerows in the Irish Landscape

Towards a National Hedgerow Biomass Inventory for the LULUCF Sector Using LiDAR Remote Sensing

CCRP Report

Prepared for the Environmental Protection Agency

by

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The EPA Climate Change 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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Executive Summary

The removal of carbon dioxide (CO_2) from the atmosphere due to land-use management and forestry could potentially be used as a mitigation option under Article 3.4 of the Kyoto Protocol. In particular, the increase in the area of hedgerows and expansion of non-forest woodland patches across the Irish landscape, together with the sink activity of existing hedgerows, could be significant with respect to accountable removal units (RMUs) under the Protocol. There is, however, no national inventory system to facilitate the reporting of hedgerow sink activities to the United Nations Framework Convention on Climate Change (UNFCCC). This desk study was initiated to demonstrate the use of Light Detection And Ranging (LiDAR) remote sensing technology and terrestrial laser scanning (TLS) for assessing hedgerow biomass, with the aim of developing a cost-effective and efficient national hedgerow carbon inventory.

A pilot study was conducted using existing LiDAR data from Frenchpark, Co. Roscommon, to develop a hedgerow classification and sampling system to assess biomass and carbon (C) sequestration by adopting a range of geo-processing techniques and empirical models. Direct modelling of LiDAR metrics, such as intensity and percentiles of 1st and 2nd laser returns, was used to accurately (RMSE[1] ± 7.3–19 t C/ha) estimate hedgerow and non-forest woodland biomass. Optimisation of LiDAR sampling techniques suggests that the minimum laser return sample density for detecting hedgerow biomass could be reduced to five returns per square metre without influencing the performance of model estimates.

Following optimisation of sampling and processing requirements, guidelines and costs for developing a national LiDAR-based inventory were established. It is estimated that the total annual cost of a national hedgerow inventory could be between €80,000 and €100,000, over a 6-year reporting cycle, but the financial impact could be substantially reduced if the acquisition and processing costs for LiDAR data are shared by governmental bodies interested in the use of LiDAR for other applications.

Preliminary estimates suggest that hedgerow and non-forest woodlands could potentially sequester 0.66–3.3 t CO_2/ha/year. These estimates exclude potential emissions associated with hedgerow management or disturbance. However, the reported estimates are within the range reported by other hedgerow studies. If these estimates are representative of national hedgerows and non-forest woodlands, this could potentially result in a net removal of 0.27–1.4 Mt CO_2/year, which would increase the total land use, land-use change and forestry (LULUCF) sink estimate by ~8–28%. However, under the current accounting framework for Article 3.4, claimed emission reductions are calculated using a net–net approach. This is done by comparison of the net removal in a given year with the net removal or emission in a reference year. For the cost–benefit analysis, the year 2000 was selected as the base year using available statistics on increases in hedgerow area to derive a net–net removal estimate of 3,000–17,000 t CO_2/year. Based on the estimated cost of a hedgerow inventory and the expected accountable removals, it is estimated that a national inventory would be cost neutral at a CO_2 market price of €6 per t CO_2. Under the *current* market conditions and the Kyoto accounting mechanism, a national hedgerow inventory would offer no cost benefit. However, it is plausible that the market demand for CO_2 and the value of Kyoto RMUs would increase when new emission reduction and burden-sharing targets come into effect post-2020.

In conclusion, a national, LiDAR-based, inventory of hedgerows is feasible and cost-effective (pending future internationally agreed accounting modalities). It is recommended that additional research and inventory capacity are required to include hedgerows into a fully compliant LULUCF inventory. For example, extensive validation and ground-truthing of LiDAR and TLS biomass estimates are required to ensure that estimates are robust and defensible in the international review process. In addition, national institutions and

1. RMSE, root mean square error.

departments should develop cohesive LiDAR survey, dissemination, and inventory policies, compatible with the Infrastructure for Spatial Information in Europe (INSPIRE) Directive, so that the costs of acquiring and processing LiDAR data for multiple users can be reduced.

1 Introduction

1.1 Background

Hedgerows and woodland habitats are an important feature of the Irish landscape due in part to their roles in biodiversity, agricultural management and potential carbon sequestration. Greenhouse gas (GHG) emission reductions in the land use, land-use change and forestry (LULUCF) sector are largely associated with forestry sinks. However, it is suggested that there could be a potential GHG mitigation potential (sink potential) in grazing land or cropland[1] following the introduction of the Rural Environment Protection Scheme (REPS), which promoted the planting of indigenous trees and development of hedgerows. Similarly, there is evidence of encroachment of hazel scrub in grazing land in the Burren landscape due to a reduction in livestock numbers. There is also evidence of alder and birch expansion on abandoned/reclaimed cutaway peatlands (Black et al., 2009b). Collectively these activities constitute an additional non-forest woody biomass sink in the Irish landscape.

Under the European Union (EU) burden-sharing agreement, Ireland will be committed to reduce its GHG emissions by 20% below the 2005 value (DEHLG, 2010). Policies and measures to enhance GHG sinks are projected to result in a reduction of ~8% below the 2005 level. Additional measures or accountable sinks are required for the 20% target to be met for the non-emission trading sectors. Emissions and removals (Kyoto removal units (RMUs)) associated within the LULUCF sector can be used as a mitigation option under the Kyoto Protocol mechanism. Article 3.4 of the Protocol allows for the accounting of emission removals (sinks) associated with management of croplands, grazing land and forests. Selection of these activities for the first commitment period of the protocol is voluntary, but likely to become mandatory. Ireland did not elect cropland and grassland management for the first commitment period due to uncertainty in the magnitude of emissions or sinks in this land-use activity and a lack of methodology to report these activities on a national basis. Under the accounting and reporting rule under Articles 7 and 8 of the Kyoto Protocol, a party may elect for a land-use management activity if it is shown to be directly anthropogenic. Clearly, the expansion of non-forest woody biomass areas, such as hedgerows, in the crop and grazing land categories meets these criteria. There has been anecdotal evidence that elements of the Irish agricultural landscape, such as hedgerows and small woodland patches, may represent a significant carbon (C) sink due to an increase in non-forest woody biomass as a direct result of the REPS. However, Ireland needs to demonstrate, via transparent inventory processes, that this 'agricultural greening' associated with Article 3.4 activities is occurring before any potential carbon sink credit can be claimed in a compliant manner.

Light Detection And Ranging (LiDAR) remote sensing technology and ground-truthing techniques could offer an ideal opportunity to utilise existing land-use policies and incentives (REPS or the proposed agri-environment scheme) to realise the potential return of investment without any added cost except for the implementation and testing of a compliant monitoring, reporting and verification (MRV) programme at a relatively low input cost.

1.2 Literature Review

Hedgerows are estimated to cover 3.9% of the Irish landscape, representing ~272 kha (Forest Service Ireland, 2007a). The REPS facilitated the planting of some 10,000 km of new hedgerow and rejuvenation of some 3,000 more (Fitzgerald, Teagasc)[2]. The increase in the area of hedgerow and expansion of non-forest woodland patches across the landscape together with

1. Cropland, grazing land and wetland management can be elected for under Article 3.4 of the Kyoto Protocol. However, Ireland has not elected for these activities due to a lack of national data and large uncertainties in the magnitude of the emission or reduction related to them.

2. http://www.teagasc.ie/areaunits/kerrylimerick/LimerickNewsletters/Irish%20Hedgerows%2003-11-09%20(%20Padraig%20Fitzgerald).pdf

the sink activity of existing hedgerows could be significant. However, loss of hedgerow habitat and degradation of hedgerows should also be considered in this context. Recent studies in the UK suggest that hedgerow biomass could sequester 0.4–1.25 t CO_2/ha/year**,** depending on hedgerow type and vegetation density (Falloon et al., 2004). Assuming an average sequestration rate of 0.7 t CO_2/ha/year, hedgerow trees in the Irish landscape could represent a sink of 200,000 t CO_2/year. This estimate excludes woodland patches that are not classified as forest or hedgerow. However, reporting and accounting for these non-forest woodland and hedgerow activities under the LULUCF sector have not been possible in the past due to:

- A lack of historic data (baseline data), which are used as a reference period for calculating GHG changes over time[3];
- No national spatial or geographic information systems to detect changes in the area of hedgerows and non-forest woody biomass over time; and
- No inventory information on biomass stock changes in these land-cover types.

The only currently available methods for assessing hedgerow biomass and carbon stock change involve detailed surveys, which record biometric attributes, from which biomass can be determined, or by destructive sampling of hedgerows (Falloon et al., 2004; Henry et al., 2009). However, these methods have not been suitable for scaling up of national estimates due to time and cost constraints. Recent remote sensing technological advances now offer the possibility of developing a national reporting system for the estimation of woody biomass in hedgerows and non-forest woodlands[4]. Completion of the Teagasc National Hedge Map (THM05) will facilitate the tracking of total area changes in hedgerows and small woodland patches. An alternative approach adopted by the National Forest Inventory (NFI) used a systematic grid sample approach to track land use and land-use change, including hedgerows. This inventory system can be rolled out to include all LULUCF activities. In tandem with these geographic information systems (GIS) and inventory advances, terrestrial laser scanning (TLS) and airborne-based laser sensing (LiDAR) methods can now be applied to hedgerows as the basis for a national inventory of woody biomass stock changes in the land cover categories (Jones et al., 2007; Stephens et al., 2007; Pascaul et al., 2008). LiDAR has been used successfully to characterise and estimate woody biomass and timber volumes in forestry systems. These include approaches such as cluster analysis (Farrelly et al., 2008) to aid in forest resource inventories. The k-Nearest Neighbour (k-NN) technique has been used in a pilot study in Co. Clare to obtain forest attributes, such as volume, stocking, diameter, height, and basal area in Ireland (McInerney et al., 2005). A more direct approach involves the use of multi-component regression analysis, where plots have been measured by both LiDAR and field measurements. LiDAR parameters (for example height observations at different percentile returns) are then used to establish a multiple linear regression for total carbon per plot. Where plots have not been measured by field teams the regression estimator is used to estimate total carbon per plot, and for the biomass carbon pools, using double or two-phase sampling procedures (Parker et al., 2004).

Since LiDAR is an aerial-based approach, hedgerow or forest structure below the canopy is not easily resolved due to limited laser penetration into, and return signals from, sub-canopy layers. Various data processing functions are required to obtain information on number of trees or attributes, such as top height or tree diameter, so that tree biomass, productivity class or volume can be determined using biomass allometric functions (Farrelly et al., 2008; Pascaul et al., 2008). Processing functions include manipulation of raw data format files to produce a canopy laser cloud, which excludes the ground layer, using a digital elevation model (DEM). There are numerous automated products available to transform raw point cloud 'LAS'

3. For most signatory countries, under the Kyoto Protocol, the reference year is 1990. However, countries may choose to negotiate a different reference period, particularly in the post-2012 scenario.
4. Non-forest land is defined as land covered by trees which is not classified as forests under the national definition of forests – areas greater that 0.1 ha, greater than 20 m in width with the potential to reach 5 m in height and a canopy closure of 20% in situ.

files into canopy digital terrain models (DTM) using Fusion software (v. 3.01 US Forest Service) or Lastools (http://lastools.com) in a GIS platform. Structural elements in the canopy DTM that do not relate to hedgerows (e.g. forests or buildings) need to be masked out from the raw data cloud using GIS manipulation by overlaying forest and urban spatial data sets. Other methods involve identification of individual tree crowns using the watershed segmentation procedure (Edson and Wing, 2011). Finally, regression models are required to estimate biomass from LiDAR-derived measurements (Stephens et al., 2007).

TLS is a ground-based technique used to provide three-dimensional (3D) digital terrain images of buildings or landscape features. This offers the potential of providing detailed laser-metric information at the sampling plot level, typically 0.1–0.01 ha in size. In forestry, TLS has been used for timber forecasting based on 3D and profile models of tree stems (Thies and Spiecker, 2004). The advantage of TLS over LiDAR is that more detailed information on hedgerow structure below the canopy can be obtained since this is a ground-based technology. The disadvantage is that multiple plots would need to be scanned to produce an accurate depiction of hedgerow wood biomass status at a national level. TLS would, however, be useful for ground-truthing LiDAR assessments or in developing ground-based biomass regression models based on destructive sampling of hedgerows.

Numerous studies have demonstrated the use of other remote sensing techniques and products for characterising hedgerow boundaries and providing assessments of hedgerow cover at various regional scales. These include the use of aerial photography based on hybrid pixel/object-based analysis approaches (Sheeren, 2009). Vannier and Hubert-Moy (2010) demonstrate the use of high-resolution remote sensing images to detect and accurately identify hedgerow boundaries in the landscape. The estimation of biomass stock changes requires assessments at much higher resolutions, which should be repeatable over various timescales. Other satellite-based sensors, such as L-band microwave backscatter, have been shown to have a reasonably strong direct relationship to above-ground woody biomass at a detection limit of 15 Mg C/ha and up to a saturation of around 50 Mg C/ha (Ryan et al., 2012). The relatively low saturation limit is, however, far below the expected range of above-ground woody biomass (0–250 Mg C/ha) expected in Irish and UK hedgerows and forests (Falloon et al., 2004; Forest Service Ireland, 2007a; Black et al., 2009a). LiDAR technologies are able to detect biomass within the ranges expected for forest or hedgerows (Stephens et al., 2007), but there have been no studies on the application of the technology for hedgerow biomass assessments.

Clearly, these new approaches are not an 'off-the-shelf' technology. Considerable testing and validation are required before the use of these technologies can provide a more cost-effective solution that can augment traditional sample-plot-based measurements. In addition, the feasibility of implementing a LiDAR-based inventory within the national GHG inventory system (Duffy et al., 2011) requires consideration of the currently used land-use classification systems and compliance in reporting GHG emissions or reductions as set out in the Intergovernmental Panel on Climate Change (IPCC) good practice guidelines. More importantly, the costs associated with development of a national system for estimating hedgerow GHG balance should ideally be justified by the potential benefits of reporting additional mitigation measures through hedgerow management. This requires careful inventory design, measurement optimisation and cost–benefit analysis before a national system can be implemented.

1.2.1 A review of hedgerow surveys and data

In this section, existing hedgerow surveys, maps and inventories in Ireland, the UK and Europe are reviewed, with the goal of establishing parameters for the creation of a valid hedgerow inventory and change monitoring programme for Ireland.

1.2.1.1 Existing surveys in Ireland

County hedgerow surveys

A number of Irish county councils, with the support of The Heritage Council, have carried out botanical and structural surveys of their hedgerow stock. The motivations behind the council surveys are varied but principally concern:

- Biodiversity issues;
- Hedgerows as landscape features; and
- Accounting for hedgerow stock.

The councils generally impose habitat survey techniques based on The Heritage Council guidelines (Smith et al., 2010). An example is the Laois County Hedgerow Survey Report (Foulkes and Murray, 2005a). This report, like most other county reports, presents the results of a 1-km tetrad survey covering approximately 1% of the county area (only a subset of hedges within each square kilometre is recorded – up to ten 30-m sections). The bulk of the survey examines the species composition of the hedges; however, some structural information is recorded – the basal area category, height, number of trees in the hedgerow, 'gappiness' and management profile, as shown in Fig. 1.1.

Co. Roscommon has also been surveyed (Foulkes and Murray 2005b), but unfortunately only one of the 1-km squares fell within our LiDAR acquisitions zones used in this desk study (see sections below); this was the Square R08 (Ballinameen) where the survey records no hedgerows (the 1-km square is bog and forest).

A survey of Dublin hedgerows in 2005 (Lyons and Tubridy, 2006) concentrated on the habitat value of species-rich hedgerows (often in parks and demesnes). This report also contains information on basal density in the form of scoring from minimum vegetation to maximum and used a twinspan analysis of these data to cluster the hedgerows into four groups based on species and structure.

There is currently no commitment to repeat the above-mentioned surveys; however, since the location of the hedgerows surveyed within each 1-km square grid is recorded, it would be possible to use these surveys as the basis of a system to monitor actual change in the hedgerow stock. Although composition and species cannot be measured by LiDAR, the structural information (hedge dimensions, height, etc.) can.

NFI of Ireland

The NFI is a stratified randomised plot sample. A 2-km^2 grid is established over the country and a random point within 100 m of the vertex is selected and land use recorded. If the land use is forestry, a permanent 500-m^2 plot is established for field visits (Forest Service Ireland, 2007b).

Whilst hedgerow is a recorded land use, the characteristics of the hedge are not recorded. As a potential source of ground-truthing for a national hedgerow map, the NFI has merits; however, as a method for estimating national cover of hedgerows, it

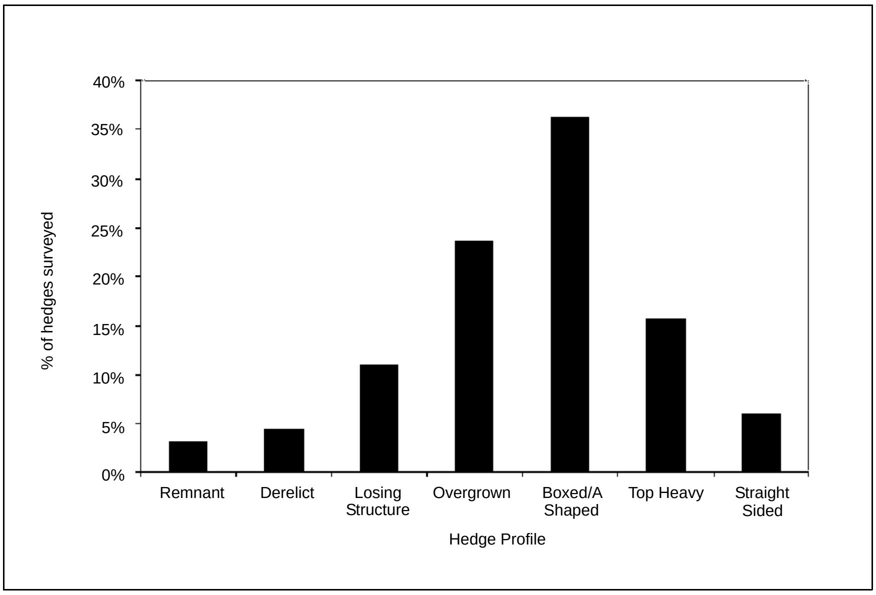


Figure 1.1. Histogram showing distribution of hedgerows in Co. Laois as a function of management type – taken from *Laois County Hedgerow Report* (Foulkes and Murray, 2005a).

is inappropriate (a point sample will always overestimate large objects and underestimate small). This random grid sample approach was adopted because there was no a priori knowledge of the distribution of the extent of the national forest. However, this is not the case for hedgerows, since a current hedgerow map does exist (THM05, see below). Therefore, the sampling approach used in the NFI would not be as efficient as other approaches, such as cluster sampling or stratified random sampling.

Department of Agriculture, Food and the Marine planting records

Locations of new hedgerows planted under the REPS (Department of Agriculture and Food (2000) and Agricultural and Environmental Structures (AES), the follow-on scheme) are recorded under the e_REPS mapping service. More than 10,000 km of hedges have been planted under this scheme.

In 2011, hedgerows were designated as landscape features and are now protected under the requirements of Good Agricultural and Environmental Conditions (GAEC). The Department of Agriculture, Food and the Marine[5] (DAFM, 2011) rules state:

*"This means that in general they **cannot** be removed. Hedgerows must also be maintained and not allowed to become invasive thereby reducing the utilisable area of the field and consequently impacting on the area eligible for the single payment. Where, in exceptional circumstances, a hedgerow must be removed as for example to facilitate farmyard expansion, a replacement hedge of similar length must be planted at a suitable location on the holding in advance of the removal of the existing hedgerow."*

Therefore, in principle, if the rules can be demonstrated to be successfully applied, future changes in hedgerows can be easily monitored (or, at the very least, DAFM records will provide a set of validation statistics).

Teagasc Hedge Map (THM05)

The THM is a remote-sensing-derived map of hedgerow and woody scrub – essentially all non-forest woody biomass (Green, 2010). The project relied upon image processing, which involves taking a digital photograph and programming the computer to automatically detect hedges in the image ('hedges' and not 'hedgerows', as traditionally hedgerow refers to the whole structure of the field boundary, not just the vegetation but the bank and ditch associated with it – in this project just the area extent of the vegetation as seen from above is mapped).

The THM project developed image processing techniques that exploited the hedgerow colour as recorded on the national ortho-photography series for 2005 and also the texture and shadows associated with hedges to classify the photographs. The project had to develop bulk processing techniques to process the 20,000 photographs that make up the national colour ortho-photography database for 2005. It built on extensive and growing literature on mapping the extent of hedgerows automatically from optical imagery (Thornton and Atkinson, 2006; Tansey and Chambers, 2009; Aksoy et al., 2010; Vannier and Hubert-Moy, 2010) and in detection of non-forest woody biomass and trees outside the forest. The results are a thematic map, with 1 m pixel size, showing all mature hedgerows, individual trees and non-forest woodland/scrub, with an estimated 80% accuracy. The map cannot be displayed at a visible scale in this document. Table 1.1 gives the estimated area under hedge/woodland in each county.

1.2.1.2 The UK experience

The *Hedgerow Survey Handbook* published by the UK Department for Environment, Food & Rural Affairs (DEFRA) (2007) outlines in detail methods for surveying hedgerows both by professional and voluntary groups. It defines hedgerows, explains their principal features and goes through the practicalities of carrying out a survey. The handbook has little to mention on sampling strategy, except that census surveys should only be carried out at a local level, with random surveying typically involving the selection of 1-km grid cells and the measurement of nine random hedgerows within the cell.

The handbook does have an extensive section describing and measuring the physical characteristics of hedges (width, shape and gappiness) with good

5. Previously the Department of Agriculture, Fisheries and Food (DAFF).

Table 1.1. Area extent of hedgerow, woodland and scrub (HWS) for each county.

County	Area of HWS (ha)	% of national HWS stock	% of county under HWS
Carlow	8,000	1.8	8.9
Cavan	20,000	4.4	10.4
Clare	22,000	4.9	7.0
Cork	57,000	12.7	7.6
Donegal	20,000	4.4	4.1
Dublin	5,000	1.1	5.4
Galway	30,000	6.7	4.9
Kerry	23,000	5.1	4.8
Kildare	14,000	3.1	8.3
Kilkenny	19,000	4.2	9.2
Laois	12,000	2.7	7.0
Leitrim	11,000	2.4	6.9
Limerick	25,000	5.6	9.3
Longford	8,000	1.8	7.3
Louth	8,000	1.8	9.8
Mayo	23,000	5.1	4.1
Meath	24,000	5.3	10.2
Monaghan	16,000	3.6	12.4
Offaly	13,000	2.9	6.5
Roscommon	19,000	4.2	7.5
Sligo	11,000	2.4	6.0
Tipperary	35,000	7.8	8.1
Waterford	12,000	2.7	6.5
Westmeath	17,000	3.8	9.2
Wexford	20,000	4.4	8.5
Wicklow	10,000	2.2	4.9

illustrations and a key to identifying structures as hedgerows (Fig. 1.2).

A report from the Institute of Terrestrial Ecology (Sparks et al., 1999) investigated issues relating to the use of the UK countryside surveys (CSs) to get reliable estimates on hedgerow stock (expressed in length) from the UK CS stratified sample (stratified on 32 land-use classes) of 1-km survey squares. They found that the approximate 0.6% land area coverage of the stratified sample could give a national estimate and that the use of a regular sampling scheme limited the use of geospatial techniques and explicitly that of spatial covariance (the amount of hedgerows in a cell is closely related to the amount of hedgerows in adjacent cells). With a priori knowledge of hedgerow

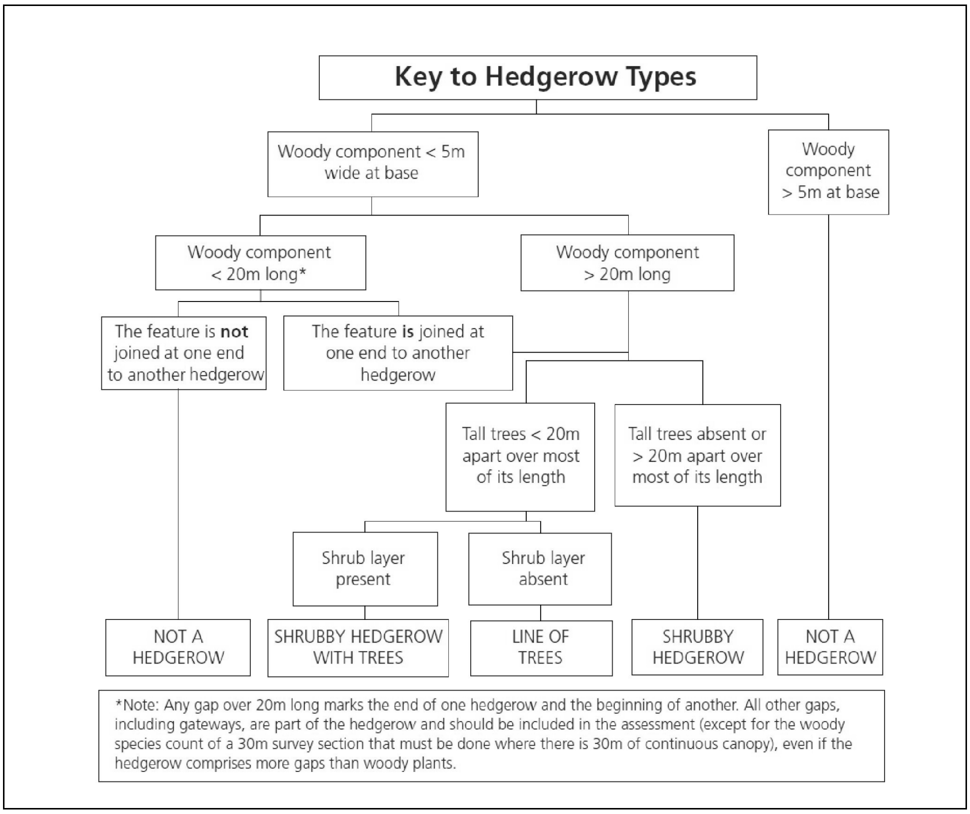


Figure 1.2. Identification key for hedgerows (extracted with permission from the UK *Hedgerow Survey Handbook* (DEFRA, 2007)).

distribution, one can devise a more focused survey and still maintain statistical validity.

The National Inventory of Woodland and Trees (NIWT) for England (Smith, 2001) used a very similar sampling strategy to survey trees and clumps of trees between 0.2 and 2 ha in size:

"*A random sample of approximately 1% of land area was taken, with the basic sampling units being 1 km squares from the Ordnance Survey grid.*"

Mapping was done using aerial photography, with some field verification (interestingly this 0.2- to 2-ha size unit was equivalent to 10% of the total forest area). Hedgerows were not included.

1.2.1.3 International approaches

Change detection of length and area of hedgerow has been carried out on a survey basis in a number of European countries, most often based around interpretation of aerial photography. Methods have been developed in Spain (Sanchez-Albert et al., 2009) and the Czech Republic (Skalos and Engstová, 2009) with degrees of success and stretching back as far as the availability of (often military) aerial photography would allow.

LUCAS

The Land Use/Cover Area Frame Statistical Survey (LUCAS) is a European survey of land use based on field-point and transect observations. It is similar to the NFI 2-km grid survey, but with every point being visited in the field where practicable and data recorded, including photographs at a 250-m transect through the point. This methodology was developed in 2006 (Jacques and Gallego, 2006) but was not applied in Ireland until 2009.

The transect approach makes the LUCAS data set very useful for estimating hedgerow distribution as linear boundaries are recorded as they are intersected. In this case, hedges are classed as conifer hedges, managed and unmanaged (hedges defined as being less than 3 m in width).

An analysis of the published data sets shows that of the 4,164 transects in the Irish data set, 2,482 contained hedges (60% of points, Table 1.2). The higher number (60%) of transects with hedges in Ireland, compared with the figure for the UK (34%), is probably due to larger fields with more stone walls and large unenclosed areas in Scotland.

Table 1.2. Hedgerow occurrence in the 2006 LUCAS survey of Ireland.

Hedge type	Number of transects where hedge type is present
Conifer	32
Managed	1,434
Unmanaged	1,405
Any type	2,482

LUCAS, Land Use/Cover Area Frame Statistical Survey.

1.3 Aims/Objectives

The primary objective of this desk study was to evaluate the use of LiDAR technology for assessing biomass change in hedgerow and woodland features. Once the application of the technology had been clearly demonstrated using an existing high-density LiDAR survey of Co. Roscommon, guidelines for an ongoing national LiDAR inventory were delivered.

The specific aims of the desk study included:

- Review of literature, IPCC good practice guidance and national systems;
- Processing of LiDAR data based on a pilot study in Co. Roscommon;
- Deriving hedgerow biomass and treemetric data from laser data;
- Optimisation of the LiDAR sampling technique to minimise sampling cost in a national survey;
- Modelling hedgerow and tree biomass based on LiDAR data;
- Demonstration of the potential application of terrestrial scanning technologies as a ground-based surrogate for LiDAR;
- Comparison of LiDAR data with satellite or Ordnance Survey Ireland (OSi)-derived GIS databases, such as the hedgerow map or the NFI;
- Design of a suitable sampling strategy for a national LiDAR survey using the national hedgerow map and NFI permanent sample data;
- Cost analysis for the implementation of a LULUCF survey using LiDAR and ground-truthing techniques, including a cost–benefit analysis; and
- Identification of future research needs.

2 Materials and Methods

2.1 Study Site

The study site was located in a 265-ha area in Frenchpark, Co. Roscommon, where Teagasc had previously commissioned a high density LiDAR flight over the area. The study area comprised a mixture of all representative land uses reported under the LULUCF sector in the National Inventory Report (NIR) (Duffy et al., 2011), including grasslands, peatlands and forests. The area also contained a significant number of hedgerows and non-forest tree cover (see Fig. 2.1).

The study area was selected because of the availability of the LiDAR data to the project. Although the availability of pre-existing LiDAR data reduced project costs, this presented some technical difficulties. Firstly, there was no ground sampling of hedgerows at the time that the LiDAR data were captured in 2009 and it was not possible to capture survey data when the desk study was initiated in 2011. This meant that biomass models could not be developed based on ground-truthed data. The other disadvantage of selecting one study area is that the area may not represent all hedgerow types occurring in the country. Finally, it should be noted that stock changes and estimation of sequestration potential are based on repeat measurements conducted over a period of 3–10 years. The lack of a repeat LiDAR survey in that same area means that other methods had to be employed to estimate sequestration potential (see methods below). However, the project scope was to demonstrate the application of the technology and not to provide a nationally robust estimate of hedgerow carbon stocks.

2.2 Description of the LiDAR Technique

LiDAR is an active remote sensing system that allows for capture and analysis of surfaces in 3D format. The laser device is usually mounted on an aircraft, which flies numerous paths over a study area. Global positioning system (GPS) technology is also used to accurately cross-reference the ground measurements using laser beams (Fig. 2.2).

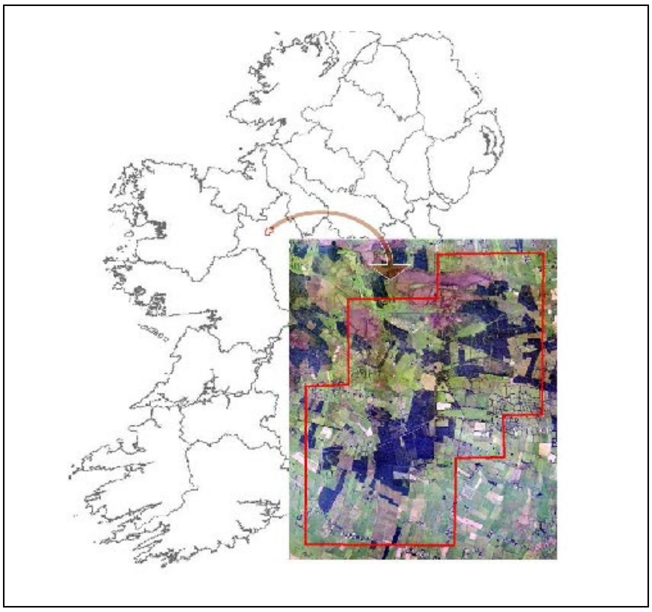


Figure 2.1. The selected pilot study area in Frenchpark, Co. Roscommon, showing the project boundary (in red) which corresponds to the flight path areas from which Light Detection And Ranging (LiDAR) data were derived in 2009.

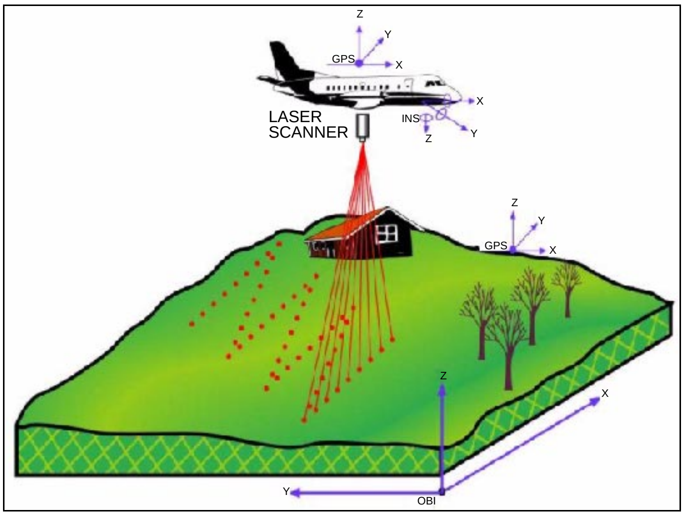


Figure 2.2. Aerial Light Detection And Ranging (LiDAR) scanning with differential global positioning system (GPS) positioning used to derive digital terrain models (taken with permission from Renslow et al. (2000)).

The rapid pulsing laser scanner emits laser pulses and measures the time for each beam to travel to and from a target, together with a record of the location of every return beam reflected from the target surface. The reflectance and scattering of the returning laser pulse are used to derive information on the location of the target, intensity of the returned signal, and distance to source, yielding x, y and z co-ordinates for each pulse returned. This information is then used to generate DTMs (Fig. 2.3) from which forest or hedgerow information can be derived (see methods below).

LiDAR data were recorded by OSi from 19 to 31 April 2009 using a Leica ALS50 II system mounted on a two-seater Piper fixed-wing aircraft (Clifford et al., 2010). The four-return system is capable of a pulse rate of 150,000 kHz. The area was flown at a height of 1,700 m. A scan angle of less than 12° off nadir was specified, with an average of seven returns/m^2. Data were received from OSi in LAS format containing the x, y, z co-ordinates of each pulse, return number, intensity and scan angle, together with a DTM. Survey parameters are shown in Table 2.1.

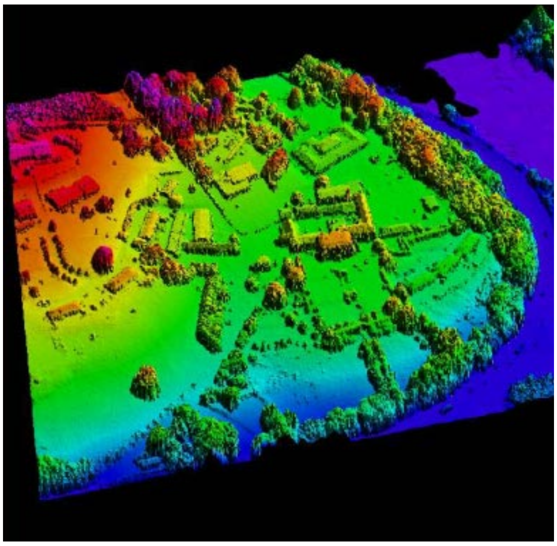


Figure 2.3. An example of a digital terrain model (DTM) showing landscape features such as buildings, forests and hedgerows.

Table 2.1. Light Detection And Ranging (LiDAR) survey parameters.

Parameters	Value
Sensor	ALS50 II
Frequency	137,300 Hz
Flying height	1,700 m
Footprint diameter	0.39 m
Scan angle off nadir	12°
Sampling density	7 returns/m^2
Elevation accuracy	0.07 m

2.3 Definition of Hedgerows and Non-Forest Woodlands

For this study hedgerows are defined as "***Linear** strips of **woody** plants with a shrubby growth form that **cover** >25% of the length of a field, lane or property boundary. They often have associated banks, walls, ditches (drains) or trees*" (Foulkes and Murray, 2005b). More detailed definitions or sub-categories may be applied at a later stage in the national inventory to include width or hedgerow type, such as managed or townland boundary hedgerows, etc. To differentiate between hedgerows and non-forest patches, which are also linear features, such as riparian woodlands, a maximum hedgerow width of 4 m was selected, based on the data cloud extraction technique (see methods below) and the definition of forest areas (Forest Service Ireland, 2007a). This definition is also consistent with the national hedgerow map, which could be used as the basis for the total national hedgerow area in the future inventory.

The national definition of forest land is an area of land where the tree crown cover is greater than 20% of the total area occupied. It has a minimum width of 20 m and a minimum area of 0.1 ha and includes all trees with a potential to reach 5 m in height in situ. Based on this definition and that of hedgerows, non-forest woodland patches can be defined as an area where tree crown cover is 20% of the total area, with a minimum width of 4 m, a maximum width of 20 m and a total area of less than 0.1 ha (i.e. wooded areas which are neither forest nor hedgerow).

2.4 Identification of Hedgerow Areas

Identification of hedgerow features and areas was done using various steps as outlined in the schematic shown in Fig. 2.4:

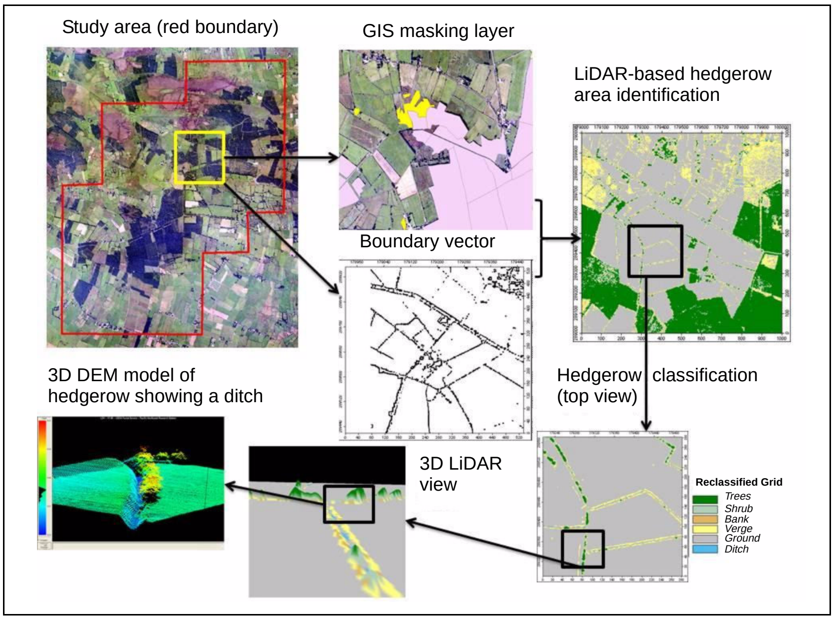


Figure 2.4. A schematic representation of the hedgerow classification and characterisation methodologies used, based on Light Detection And Ranging (LiDAR) and other geographic information systems (GIS) resources for the Frenchpark region (see text for descriptions). DEM, digital elevation model.

(a) **Masking layers:** Creating and compiling digitised vector layers of forests (FIPS2007, Forest Service), urban layers and other woodland patches. This was used to mask out vegetation classes that may be similar to woodlands in terms of elevation profiles. For example, forest trees or settlements are reported under different LULUCF categories, so those features with a height greater than 1 or 2 m may be misclassified as hedgerows or double accounted in LULUCF area matrices. Polygons representing areas afforested after 2007 were merged into the Forest Inventory and Planning System (FIPS) (FIPS2007, Forest Service) layer to create a forest mask of all forest areas up to 2009 (FIPS2009, Forest Service), which corresponds to the time when the LiDAR data were obtained. Non-forest woodland patches were manually digitised using OSi aerial photographs.

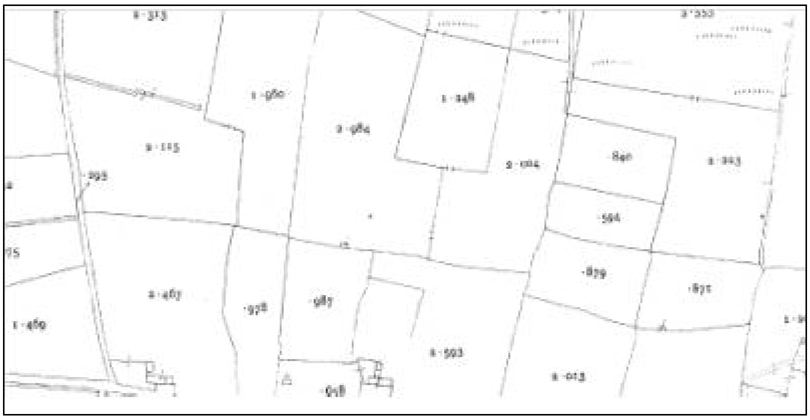
(b) **Use of land boundary vector to derive linear hedgerow areas:** Hedgerow areas were defined using a boundary edges detection algorithm. A high-pass filter algorithm was used to classify areas based on change in height, or intensity of laser pulse returns across a predefined land boundary. In the absence of a national field boundary layer, one had to be created based on the old 25" OSi maps. The steps for generating field boundary samples were:

(i) Mosaic 25" sheets over area (Fig. 2.5a);

(ii) Perform 5 × 5 pixel morphological dilation over the mosaic (this has the effect of closing small gaps, due to scanning errors, and thickening lines) (Fig. 2.5b);

(iii) Clumping (eight neighbours) and sieving with a minimum 10,000 pixel size (this eliminates most of the symbology and writing) (Fig. 2.5c);

(a)



(b)

Figure 2.5. Steps for generating field boundary samples.

(c)

(d)

(e)

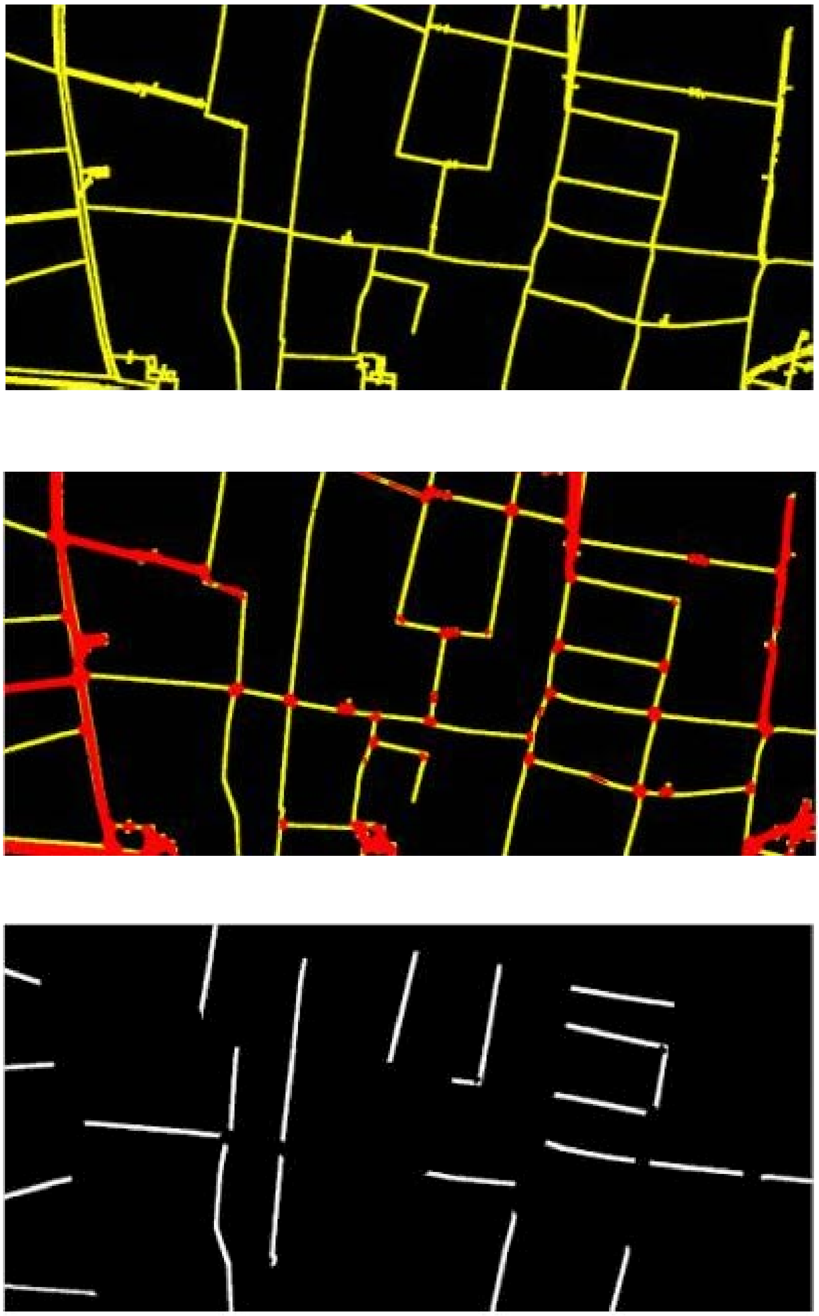


Figure 2.5 ***contd***

(iv) Reset all clusters to 1 – thus creating a 1-bit boundary/non-boundary file;

(v) In order to break the continuous boundary into segments, identify corners and non-boundary line work (roads, etc.) by convolving a suitably sized kernel (21× 21) and identify all those with a sum >50% (in red, see Fig. 2.5d);

(vi) Buffer out by 3 pixels to create a 'corner mask'; and

(vii) Mask boundary file with corner mask clump and sieve to get rid of small segments to create boundary file (Fig. 2.5e).

It is important to remember that this is not intended to create a mask of all field boundaries but to reliably identify a large sample of field boundaries with a very low commission error from which LiDAR data can be extracted to represent hedgerow boundary samples within the study area. It seems likely that any future project will have access to the OSi Prime2 database, which will provide an up-to-date set of vector field boundaries.

(c) The hedgerow was then further classified into trees (>2 m), shrubs, ditches, verges and vegetation. This was used to characterise area (2D) assessment laser-metric information (3D) used in the estimation of biomass (see Fig. 2.4).

(d) Once hedgerow areas were identified, further analysis was required to differentiate between elevated or depressed features such as banks, ditches or roads. Failure to do this would result in the overestimation of hedgerow height, volume or biomass.

2.5 Deriving a Canopy DEM for Hedgerows

Hedgerow line features (see Section 2.4, Step b) were used to create a polygon layer using a 2-m buffer, creating 4-m-wide lozenge-shaped polygons around the field boundary to sample hedgerow laser data clouds. Sampled point cloud raw data were transformed into a canopy DEM using two different methods, depending on the tree height sampling method used. A canopy height model (CHM) is a continuous interpolated surface representing the top of the vegetation. For the crown segmentation method (Section 2.6.1), a canopy DEM was obtained from LiDAR raw point cloud LAS files using Fusion software (v. 3.01 US Forest Service). An average point spacing of 1.88 m and a filter for window smoothing of 3 × 3 cells were used. For the random tree sampling method (Section 2.6.2), the LAS file was initially clipped using the hedgerow boundary sample polygons. The clipped LAS file was converted to ASCII format using lastools (http://lastools.com) and projected in ArcGIS v. 9.3. All points with a height of greater that 1.5 m were selected and transformed to a DEM using a raster resolution of 1 m and a filter for window smoothing of 3 × 3 cells. The raster height values (Z) were assigned the highest Z value to represent the top of the hedgerow canopy, using the 3D analyst in ArcGIS v. 9.3.

2.6 Sampling the Canopy DEM for Treemetric Data

2.6.1 Method A – Identification of individual crowns

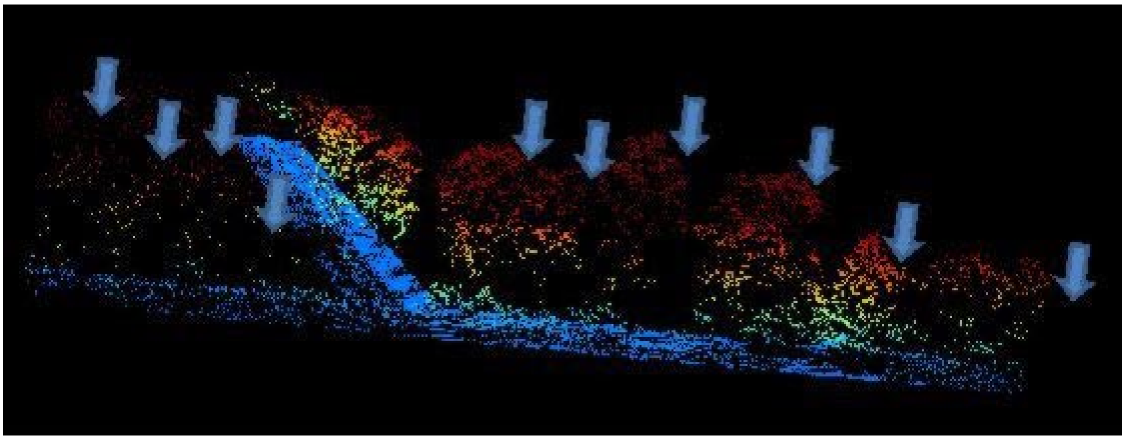
The derived canopy DEM (using Fusion software, see above) was processed using the watershed segmentation procedure (Edson and Wing, 2011) using SAGA software (freeware downloaded from http://sourceforge.net/projects/saga-gis/). The canopy height rasters were smoothed using a Gaussian grid filter with a search radius of 3 m. The grids were then segmented using the height maxima method in SAGA. The centroid point of the derived polygons for each individual crown was used to sample the DTM raster using the ‘raster values from points’ tool in ArcGIS v. 9.3.

2.6.2 Method B – Random sampling

Tree heights were randomly sampled by creating random points within the hedgerow boundary polygon using the random point tool in ArcGIS. The number of random points within each hedgerow boundary polygon was determined by the area of the hedgerow and a 2-m predefined minimum distance between points. Sensitivity analysis was carried out by varying the minimum distance between points from 1 m to 5 m. The number of derived sample points was compared with the frequency of crown centroids derived using Method A above. A minimum distance of 2 m between random points correlated best with the crown centroid frequency across 354 hedgerow samples. The 2-m random sample point files were used to sample the DEM raster, using the ‘raster values from points tool’ in ArcGIS v 9.3. The reprocessing functionality was set up in the ArcGIS model-builder to facilitate bootstrapping, where 1,000 sample iterations were run to return height samples. The derived height for each iteration was converted to above-ground biomass using Eqn 2.1 and the mean hedgerow biomass was calculated from the 1,000 interactions. Preliminary comparison of means shows that the resulting mean of cumulative iteration runs was not significantly different after 25 iterations.

Figure 2.6a and b shows a comparison of crown position in the raw point cloud data and the derived crown position using the watershed segmentation

(a)



(b)

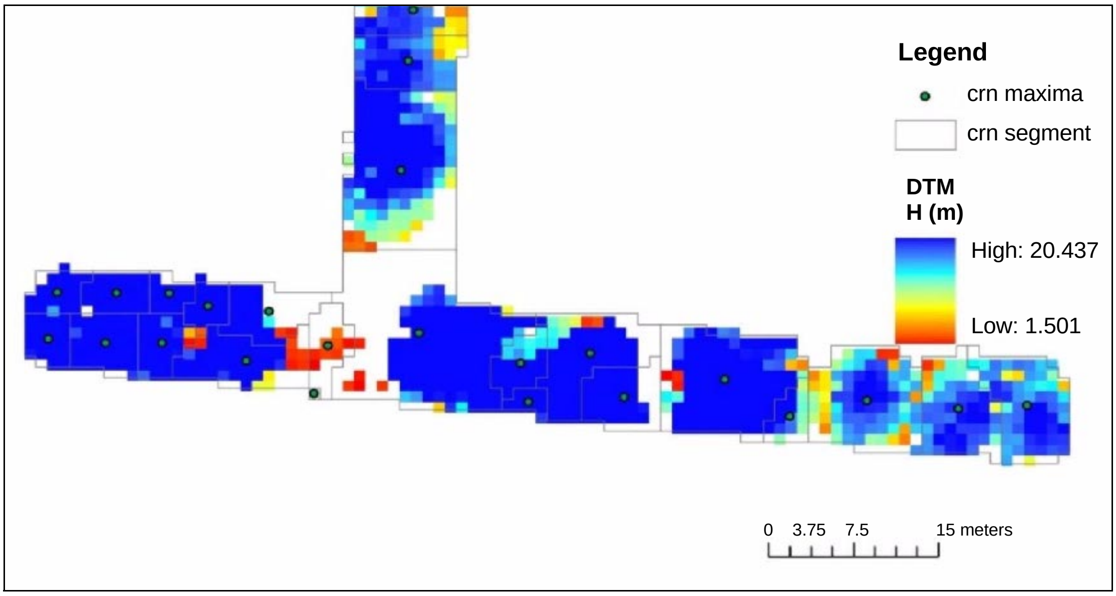


Figure 2.6. (a) The raw laser point cloud data showing the position of crown tops in a selected hedgerow polygon (as indicated by blue arrows). (b) The derived canopy digital elevation model (DEM) showing the hedgerow height (H) on a 1-m grid. The crown segment polygon (crn segment) represents the derived individual crowns. Each crown is represented by a height maxima (crn maxima), which is the polygon centroid point used to sample the DEM to derive tree height. DTM, digital terrain model.

approach. This comparison shows that crowns are well characterised, but double crowns are identified in some cases, particularly in canopy tops with little variation in height (see tree on the left-hand side of Fig. 2.6a and b).

2.7 Derivation of Biomass from Tree Height

Above-ground biomass was derived using an algorithm developed from harvested broadleaves as described in the CARBWARE forest model (see Duffy et al., 2011; Black et al., 2012). The algorithm was refined to provide above-ground biomass (AGB) (measured in kg C) based on tree height (*H*) derived from the segmentation of tree crowns or randomly sampled tree heights:

$$AGB = 0.179 \times H^{3.3} \qquad \text{Eqn 2.1}$$

The carbon (*C*) fraction for biomass determinations was assumed to be 50% (Black and Farrell, 2007). Broadleaf algorithms were selected because over 95% of trees and hedge species in hedgerows located in Roscommon are broadleaves, primarily ash and whitethorn (Foulkes and Murray, 2005b).

2.8 Direct Derivation of Biomass from Laser Return Statistics

A more direct approach to derive biomass is directly from laser-metric data based on regression analysis against biomass estimates. A major national developmental requirement is a direct biomass sampling of hedgerows directly after LiDAR assessments. These data could be used to model biomass based on laser-metric data. However, being a desk study, this was outside the scope of the current project. This study explored the applications of LiDAR data to directly determine biomass for scaling up to the national or regional level. To this purpose, multiple regression analyses of derived biomass estimates (as described above) against LiDAR metrics, such as mean height at a determined percentile return, number of laser returns above 0, 0.5 and 1.5-m heights, and the density of the point clouds were carried out using bivariate correlation analysis (IBM SPSS Statistics v. 19). All variables were checked for normality and normalised using log transformation if required before correlation analysis.

The clipped LAS files (see Section 2.4) for each hedgerow length were used to derive descriptive statistics, including hedgerow polygon area, number of total first, second, third and fourth returns, mean height and laser intensity returns at percentile return at 10% bin sizes. The statistics were run using pre-selected height values of zero (ground level), 0.5 and 1.5 m above the ground to assess the error introduced by including ground returns under the hedgerow canopy after ground returns have been removed from the canopy point cloud.

Once the significant key determinant laser-metric parameters were established, a non-linear mixed effect model was developed using algorithms in the SAS NLMIXED procedure (SAS, 2008). All coefficients and partial coefficients were determined using least squares optimisation in SAS. The final algorithm format for hedgerows (shown in Eqn 2.2a) represents a culmination of extensive testing of model formats and the dropping of parameter terms from the model if parameter coefficient variables were determined not to be significant.

$$AG = a0 \times a1 \times (a\mu \times \mu\,(1 - \mathrm{Exp}(a\mathrm{E.P70} \times \mathrm{E.P70}^{(a2 + aR \times R)}))) \qquad \text{Eqn 2.2a}$$

where AG is expressed in t C/ha. Terms *a*0, *a*1 and *a*2 are residual scaling coefficients. The term *a* is a coefficient variable for parameters µ, E.P70 and *R* (see Table 2.2 for definition of parameters).

The same analysis was carried out for woodland patches, but the form of the equation varied because some laser-metric variables showed no significant relationship with biomass. Inclusion of the variable *R* did not improve the performance of the model, so this term was dropped from the model (Eqn 2.2b). The final equation for direct estimation of biomass (t C/ha) for the woodland patches was:

$$AG = a0 + a\mu \times \mu \times a\mathrm{E.P70} \times \mathrm{E.P70} \qquad \text{Eqn 2.2b}$$

Performance of model calibration was assessed using root mean squared error (RMSE) and accuracy (a measure of bias):

$$RMSE = \sqrt{\sum_{1}^{n} \frac{(x_i - X_i)^2}{n - p}} \qquad \text{Eqn 2.3}$$

Table 2.2. Description of used laser-metric model parameters, including all point data above 0, 0.5 or 1.5 m in height.

Laser-metric variable	Abbreviation	Derived from
Density and structure of hedgerow	µ	Ratio of 2nd to 1st returns
Density of hedgerow	*R*	Number of returns/m^2
Mean height	e.g. E.P70	Mean elevation of the 70th percentile return
Laser intensity	e.g. I.P70	Mean laser intensity of the 70th percentile return

where x_i is the predicted value, X_i is the observed diameter increment, p is the number of parameters used and n is the sample number.

The average residual of model accuracy (e') was estimated from observed and predicted residuals:

$$e' = \sum_{1}^{n} \frac{(x_i - X_i)}{n} \qquad \text{Eqn 2.4}$$

from which the accuracy (a measure of bias) is derived as the quotient of e' and the number of observations (n). The percentage accuracy is expressed as e' *divided by* mean observation value *(m)*.

The Wilcoxon signed-rank test was used to test for significant differences between the observed and predicted values (SPSS v. 19). The null hypothesis (mean of residuals is equal to zero) was rejected where the P value of Z was >0.05.

2.9 Estimating Hedgerow Sequestration Potential

Estimation of hedgerow above-ground sequestration potential was done using two approaches:

1. Stock change approach using the derived biomass values assuming a steady-state transition; and

2. Simulation of above-ground gains and losses using the CARBWARE model (Duffy et al., 2011; Black et al., 2012).

Neither approach considers the loss of biomass associated with hedgerow management due to trimming of hedges or complete removal of hedgerow. This estimate would reflect the potential sequestration of hedgerows if they were unmanaged. The sequestration potential estimates do not consider the additional sequestration potential associated with planting of new hedgerow areas.

2.10 Deriving Non-Forest Woodland Patch Biomass and Sequestration Potential

A sample of non-forest woodland patches was derived by manually digitising polygons using the aerial photographs and the FIPS 09 data as a guide. Estimation of non-forest woodland biomass was done as described for hedgerows (Section 2.5), but only using Method A in Section 2.6 (i.e. crown segmentation to derive crowns and tree height and tree number). Tree biomass was derived from tree heights and directly from laser-metric data as outlined in Sections 2.7 and 2.8.

For estimation of sequestration potential both the steady-state and gains–loss approach were used. For the gains–loss approach, the CARBWARE model was used using the fast-growing broadleaf species cohort sub-model (Duffy et al., 2011; Black et al., 2012).

2.11 TLS Scanning of Sampled Hedgerows

2.11.1 Description of TLS

TLS is an accurate method used for the measurement of 3D structures and is widely used in architecture and process engineering. TreeMetrics has adapted this technology and developed specific software AutoStem Forest™ to process this laser scan into forest inventory specific data.

The laser scanner used by TreeMetrics was the FARO Focus 3D (Fig. 2.7). This lightweight (5 kg) portable laser scanner collects a hemi-spherical scan with approximately 40 million data points in 3.5 min, with a file size of ~145 MB at its default setting. This setting provides laser point readings every 3 mm at 10 m distance. The scanner contains its own battery supply, which provides enough power for 8 h working. The scanner is operated by a user-friendly touch-screen interface and data are stored on a removable SD card. Each scan is given a unique ID with a date and time stamp.

Figure 2.7. Terrestrial laser scanner.

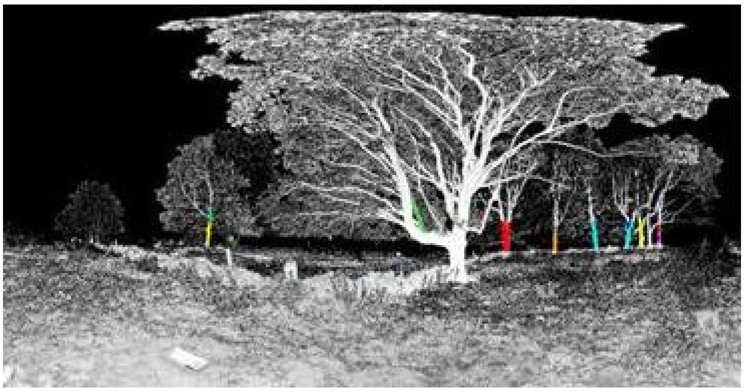


Figure 2.8. Image of 3D terrestrial laser scan with stem detection (shown as coloured regions overlaid on the tree stem) in AutoStem Forest™.

Figure 2.9. A photo of the hedgerow, corresponding to the scan shown in Fig. 2.8.

This scanner works on a phased shift method, which means that it analyses the wavelength of the laser beam to generate a 3D point cloud. The TLS can record information to 70 m in distance but the general maximum radius used by TreeMetrics is 15 m.

AutoStem Forest™ is an innovative software product developed by TreeMetrics, designed to detect and determine the volume and create a timber profile model of each tree from TLS scan data (Figs 2.8 and 2.9).

2.11.2 Surveys

After the variations of hedgerow types were identified from the LiDAR and cartographic data, one of each of the following hedgerow types were selected:

- Internal field hedgerows;
- Roadside hedgerows;
- Mature tree hedgerows; and
- Clumps of trees/hedgerows.

For efficiency of data collection, a list of suitable locations with aerial imagery and GPS co-ordinates was prepared prior to the field visit. From this list, the most suitable hedgerows were selected. For example, the roadside hedgerow was selected where there was very little traffic and there was a clear line of sight for any oncoming traffic. Approximately 20 m of hedgerow were selected for TLS at each location.

2.11.3 TLS scanning of hedgerows

Once the final hedgerow locations for the TLS were selected, the Faro 3D laser scanner was positioned at three different locations along each side of the hedgerow (see yellow locations in Fig. 2.10).

In conjunction with the TLS locations, target globes (Fig. 2.11) were positioned 1.5 m above ground using steel rods. At least three target globes need to be visible from each TLS position. The target globes are positioned within the scanning area so that scans can be automatically stitched together at the data processing stage.

Scans were completed in August 2012 before leaf senescence. Once data were collected, images were processed and analysed used the single tree detection software. This aspect of the project was only concerned with a demonstration of the technology to see if TLS can (a) detect individual trees within a hedgerow so that diameter and height can be used to infer biomass, or (b) determine hedgerow volume.

2.12 Scoping of a National System

In order to develop a national reporting system for hedgerows the following features are required:

- Extraction of laser data to derive biomass estimates (see sections above);
- In order to test boundary information at survey level, a national sample of field boundaries is needed (see Section 2.4 (b) above);
- In keeping with the project definition of hedgerow, a sample plot of a 4-m buffer around each field

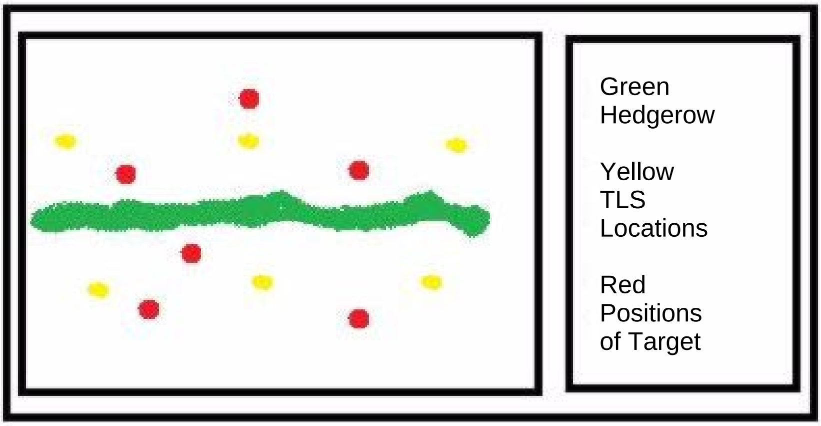


Figure 2.10. Diagram displaying the positioning of terrestrial laser scanner (TLS) (in this case six scan positions shown in yellow) and target globes (red positions).

Figure 2.11. Photo of target globe within the scan area.

boundary was created and standard forestry LiDAR plot metrics were calculated;

- Optimisation of LiDAR sampling technique to minimise sampling cost in a national survey;
- Design of a national LiDAR survey;
- Scaling provisional sequestration estimated to the national level to estimate potential carbon dioxide reduction savings to the Exchequer; and
- Cost–benefit analysis.

2.12.1 Optimisation of LiDAR sampling technique

As part of the cost analysis, the sampling frequency of the LiDAR returns required to accurately provide useful determinants of biomass was investigated using progressive decimation and LiDAR sampling optimisation. The initial sampling frequency of the Frenchpark data was 10 returns/m^2; some of the laser returns were randomly removed to determine if accuracy is maintained whilst reducing the cost of survey.

3 Results

3.1 Characterising Hedgerows

In keeping with the project definition of a hedgerow, a sample plot of a 4-m wide buffer around each field boundary was created and standard forestry LiDAR plot metrics were calculated. Figure 3.1a shows the derived hedgerow boundary polygon used for sampling LiDAR data points and the derivation of laser-metric statistics used in estimating biomass and sequestration potential. An overlay of the boundary polygon with an aerial photograph shows that a good representative sample of hedgerows can be obtained (Fig. 3.1b)

(a)

(b)

Figure 3.1. (a) Distribution of boundary samples (non-forest areas). (b) Intersection of boundary lozenges with aerial photography.

Data manipulation of the raw data (DEM) was required to differentiate between elevated and depressed features, such as banks, ditches or roads. Failure to do this would result in the overestimation of hedgerow height, volume or biomass. This was successfully done by constructing a ground layer elevation model (DEM) with ditches, road, etc. (Fig. 3.2). However, the high slope of ditches and banks decreases the quality of the terrain model in these areas, thus it can increase the error for the height vegetation estimation.

The DTM classification was done using the following detection limits:

- Ditches: <–0.15 m;
- Ground: –0.15 to 0.1 m;
- Verges: 0.1 to 0.3 m;
- Banks: 0.3 to 0.5 m;
- Tall shrubs and fences: 0.5 to 1.5 m; and
- Other trees and shrubs: 0 to 1.5m.

An additional height cut-off for hedgerow vegetation of 1.5 m was also imposed to reduce the amount of ground returns remaining in the canopy elevation model. This was further justified following correlation analysis of laser statistics from 0, 0.5 and 1.5-m data exclusions with estimated biomass values (see Table 3.1).

3.2 Biomass of Hedgerows Based on Tree Height

The estimated biomass density of sampled hedgerows produced similar results when the two sampling methods were compared (Table 3.1). Paired *t* tests suggest that the means are not significantly different.

3.3 Biomass Estimation Based Directly on Laser-Metric Parameters

Correlation analysis identified the performance of biomass estimates, based on Pearson correlation coefficients for laser-metric parameters at zero, 0.5

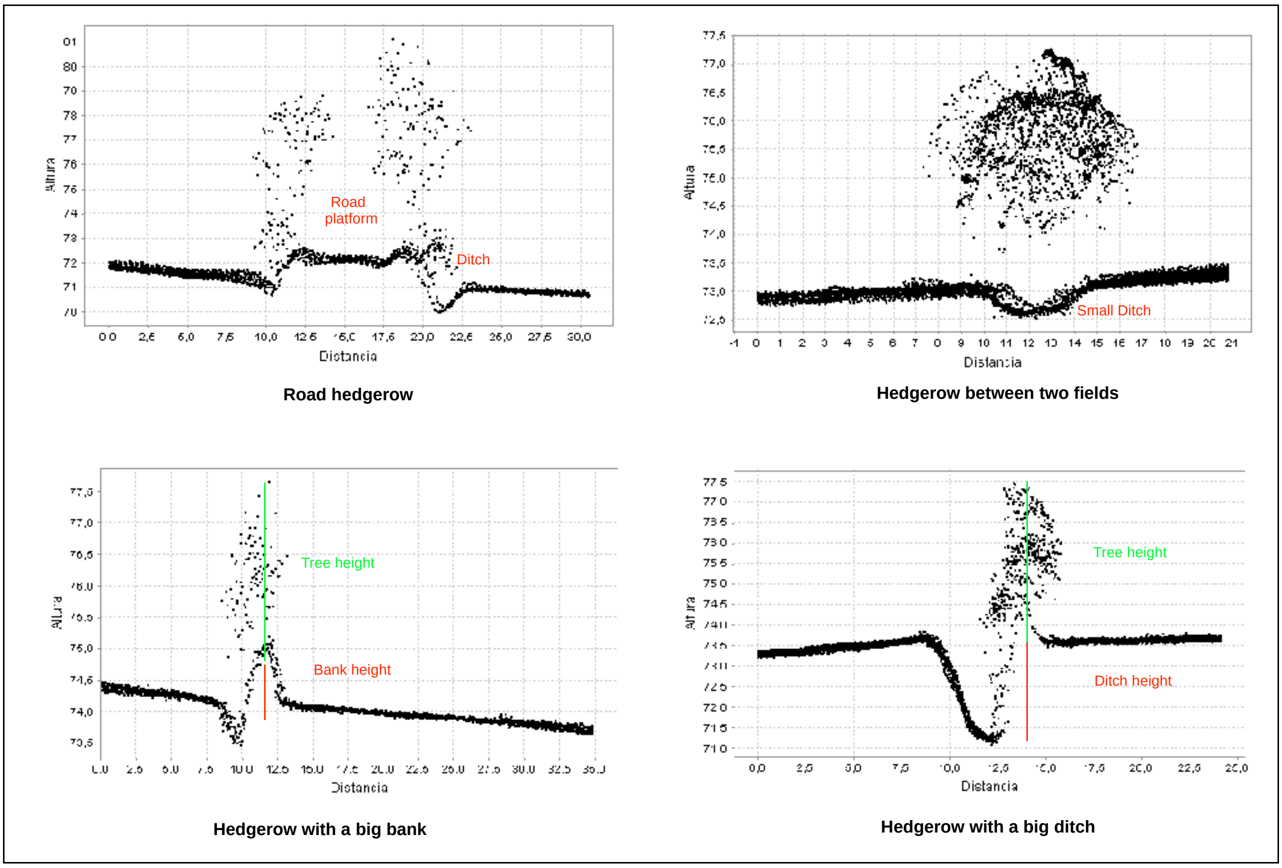


Figure 3.2. Side view (2D) of digital elevation model (DEM) demonstrating the detection of banks, ditches and roads in linear hedgerow features.

Table 3.1. Descriptive statistics of estimated above-ground biomass density (t C/ha) derived using Method A (crown segmentation) and Method B (random point sample).

Statistic	Method A	Method B
N (number hedgerows tested)	228	228
Range	0.01–349.35	0.01–298.82
Mean (SE)	21.06 (3.18)^{ns}	19.93 (2.99)^{ns}
Standard deviation	39.54	37.15
Skewness (SE)	4.94 (0.19)	4.29 (0.19)
Kurtosis (SE)	34.13 (0.39)	24.92 (0.39)

ns, not significant – comparison of means using the paired *t* test indicates that the means were not significantly different at the 95% confidence interval.
SE, standard error.

and 1.5 m as shown in Table 3.2. A minimum of 1.5 m above the ground was selected for further analysis because (a) the correlation between laser-metric data and biomass estimates was stronger for the data set with a minimum height above ground of 1.5 m, (b) the mean height value was significantly reduced at higher percentile returns, and (c) the authors wanted to exclude the influence of non-woody biomass from the

Table 3.2. Pearson's correlation coefficient for estimated biomass and laser-metric parameter relationships using statistics from pre-selected minimum heights of 0, 0.5 and 1.5 m.

Laser-metric variable	Pearson's correlation coefficients for data with a minimum height at:		
	Ground level (0 m)	<0.5 m	<1.5 m
μ	0.52^{b}	0.59^{b}	0.72^{a}
R	$–0.102^{ns}$	0.378^{b}	0.464^{b}
E.P20	$–0.02^{ns}$	$–0.11^{ns}$	0.301^{ns}
E.P50	0.214^{ns}	0.321^{b}	0.49^{b}
E.P70	0.307^{b}	0.415^{b}	0.60^{a}
E.P90	0.211^{ns}	$0.398^{\mathbf{b}}$	$0.57^{\mathbf{a}}$
I.P20	$–0.182^{ns}$	0.154^{ns}	$–0.08^{ns}$
I.P50	0.09^{ns}	$–0.111^{ns}$	$–0.26^{ns}$
I.P70	$0.39^{\mathbf{b}}$	$–0.198^{ns}$	$–0.29^{ns}$
I.P90	$–0.28^{ns}$	10	$–0.28^{ns}$

[a]Indicates a significance at P < 0.01.
[b]Significant at P < 0.05.
ns, Not significant, where P > 0.05.

analysis. This would also partially remove the effect of walls, ditches and banks on the estimation of biomass.

Based on preliminary analysis of scatterplots, it can be seen that the relationships between laser-metric variables and biomass are not linear (Fig. 3.3). This necessitated the development of a non-linear mixed effect model as described in Chapter 2.

The derived model describes the variation in biomass as a combined function of hedgerow density, structure and height using the three parameters shown in Fig. 3.3. The single use of the parameter *mean H* at the 70th percentile return does not describe the variation in hedgerow biomass when the vegetation cover is sparse within a hedgerow polygon, for example, as seen on the scatterplot in Fig. 3.3, where hedgerows with higher mean heights correspond to low biomass values due to a small number of trees or hedges in a hedgerow boundary. Clearly, the combined use of parameters describing density and height would be particularly useful to provide a more accurate estimation under these situations.

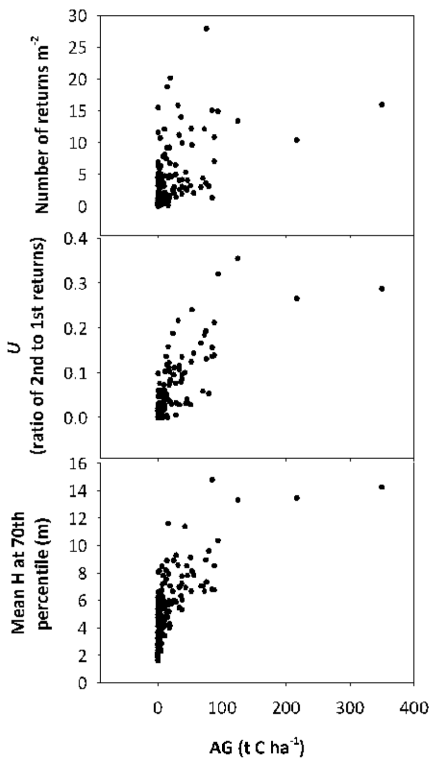


Figure 3.3. Scatterplots of the predictive laser-metric parameters (above 1.5 m) used in the non-linear mixed biomass model.

The Wilcoxon signed-rank test of observed and predicted biomass values indicates that the null hypothesis can be rejected at a significance interval of

Table 3.3. Estimated model parameter (see Eqn 2.2a) coefficients and goodness of fit for hedgerows. All fitted parameters (unitless) were significant at P < 0.05. The root mean squared error (RMSE) is a measure of precision or absolute variance expressed in t C/ha. Accuracy as a measure of bias is expressed in t C/ha, with the percentage value in parentheses.

Model parameters in Eqn 2.2a	Value
*a*0	5.12
*a*1	4.02
*a*2	0.70
*a*μ	–29.99
*a*E.P70	0.24
a.R	0.012
Goodness of fit	
RMSE	19.45
Accuracy	–2.20 (–12%)
P value	<0.01

greater than 99%, suggesting that there is no difference between the mean of the observed and predicted data (Table 3.3). However, measures of goodness of fit show a relatively large residual variance (RMSE of 19.45 t C/ha) and a negative bias of predicted values, suggesting that predicted values would, on average, underestimate the mean biomass of the sampled hedgerow population by 12%.

3.4 Estimation of Above-Ground Sequestration Potential

3.4.1 Steady-state transition approach

Biomass density (i.e. t C/ha) of the sampled hedgerow population in Frenchpark varied from 0.01 to ~350 t C/ha (Table 3.1), with more than 50% of hedgerows having a biomass of less than 4 t C/ha. The biomass gains potential, as estimated using the mean value in the 75th percentile (Henry et al., 2009), were 45 and 49 t C/ha for Methods A and B, respectively. This potential sequestration estimate does not consider loss of biomass due to hedgerow management, but indicates a potential gain for a newly established hedgerow of ~0.9 t C/ha/year if the IPCC good practice default transition time of 50 years is assumed (Falloon et al., 2004). This equates to a potential of 3.3 t CO_2/ha/year in newly established non-managed hedgerows.

3.4.2 Gains and losses

The CARBWARE model estimates individual tree growth (gains) based on height and diameter increment and losses due to natural mortality and litterfall as described by Duffy et al. (2011). Single tree increments were aggregated to the hedgerow area and normalised on an area basis. The mean estimated sequestration potential of above-ground biomass was 0.18 t C/ha/year, equivalent to 0.66 t CO_2/ha/year for the sampled area in Frenchpark. There was a high frequency of hedgerows with a very low sequestration potential (Fig. 3.4a) due to a low hedgerow tree density and initial biomass values. The relationship between sequestration potential and biomass suggests that the state transition from young to mature hedgerows is not linear (Fig. 3.4b). These estimates also suggest that the steady-state transition approach may overestimate

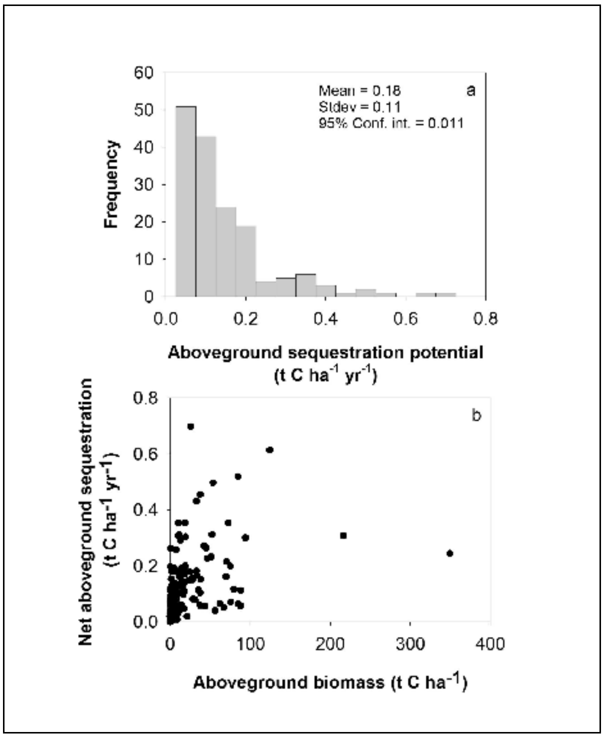


Figure 3.4. (a) The frequency distribution of above-ground carbon gains for the Frenckpark hedgerow sample, as estimated using the CARBWARE model, and (b) the relationship between sequestration potential and hedgerow biomass.

sequestration potential because of the non-linear dynamic and the longer transition period required to reach steady-state sequestration potential.

3.5 Biomass and Sequestration Potential of Non-Forest Woodlands

A total of 91 non-forest polygons were digitised from aerial photographs, with areas ranging from 0.05 to 3 ha. Some of the areas were greater than the 0.1-ha threshold as specified in the non-forest woodland patch definition (Section 2.3). However, these were included in the analysis because they were not included in either the forest or hedgerow areas.

The multiple regression model (Eqn 2.2b) were re-parameterised for the non-woodland patches to derive a direct estimate of above-ground biomass from laser-metric statistics (Table 3.4.)

The biomass density of the sampled woodland patch population in Frenchpark varied from 4.2 to 57.2 t C/ha (Table 3.5). The potential biomass gain, as estimated using the mean value in the 75th percentile (Henry et al., 2009), was 39 t C/ha using Method A (see Section 2.10). This potential sequestration estimate does not consider loss of biomass due to woodland management or disturbances, but indicates a potential gain for a newly established hedgerow of ~0.78 t C/ha/year if the IPCC good practice default transition time of 50 years is assumed (Falloon et al., 2004); this equates to a potential of 2.86 t CO_2/ha/year in non-managed or undisturbed non-forest woodland patches.

Table 3.4. Estimated model parameter (see Eqn 2.2b) coefficients and goodness of fit for woodland patches. All fitted parameters (unitless) were significant at P < 0.05. The root mean squared error (RMSE) is a measure of precision or absolute variance expressed in t C/ha. Accuracy is a measure of bias expressed in t C/ha, with a percentage value in parentheses.

Model parameters in Eqn 2.2b	Value
*a*0	0.001
*a*µ	6.53
*a*E.P70	0.51
Goodness of fit	
RMSE	7.3
Accuracy	–1.3 (–7%)
P value	<0.001

Table 3.5. Descriptive statistics of above-ground biomass density (t C/ha) of estimated non-forest woodland patches derived using the crown segmentation method (Method A).

Statistic	Method A
N (number woodland patches tested)	91
Range	4.2–57.2
Mean (SE)	21.06 (1.34)
Standard deviation	12.85
Skewness (SE)	0.89 (0.11)
Kurtosis (SE)	0.18 (0.01)

SE, standard error.

The CARBWARE model estimates individual tree growth (gains) based on height and diameter increment and losses due to natural mortality and litterfall as described by Duffy et al. (2011). The mean estimated sequestration potential of above-ground biomass for non-forest woodland patches and scrub was 0.66 t C/ha/year, equivalent to 2.4 t CO_2/ha/year for the sampled area in Frenchpark. The higher and more uniformly distributed sequestration rates in woodlands compared with hedgerow (Figs 3.4a and 3.5a) were due to a higher woodland tree density and more even distribution of tree density. The relationship between sequestration potential and biomass suggests that the state transition from sampled young to mature non-forest woodland patches is linear (Fig. 3.5b). In contrast to the hedgerow analysis, estimates for woodland patches show a good agreement between the steady-state and gains–loss approaches (i.e. 0.78 compared with 0.66 t C/ha).

These estimates exclude any vegetation below 1.5 m (i.e. the detection threshold), such as crops. However, it is possible that this method could include small forest parcels not included in the FIPS09 data set.

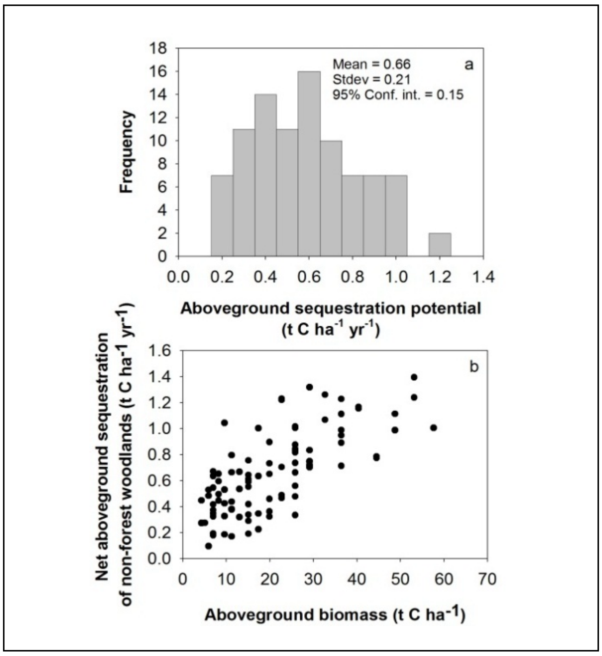


Figure 3.5. (a) The frequency distribution of above-ground carbon gains for the Frenckpark non-forest woodland sample, as estimated using the CARBWARE model, and (b) the relationship between sequestration potential and woodland biomass.

3.6 TLS

3.6.1 TLS data processing

Downloaded TLS scans were processed by TreeMetrics staff using the following three steps:

1. **Filtering:** As the laser scanner can record information up to 70 m away, the laser scan is filtered to remove noisy data and recordings outside the study area.

2. **Merging of scans:** The scans are registered using the target globes so that a full view of the hedgerow can be obtained from all directions. Single scans only record data from the position of the scanner; therefore, by merging multiple scans, a full registration of the point cloud can be obtained. Upon completion of merging the scans the images look like that in Fig. 3.6.

3. **Tree detection:** Trees are detected from the point cloud and their x,y positions are recorded. Tree size and shape are also recorded.

Figure 3.6. Ground-level view of merged laser scan.

3.6.2 Outputs

The main output from the TLS process is a full 3D model of the hedgerow (Fig. 3.7). Each object in the hedgerow had x and y co-ordinates and from these the corresponding width and height of the hedgerow can be calculated. Therefore, hedgerows with a high density of points per square metre will have a higher biomass density.

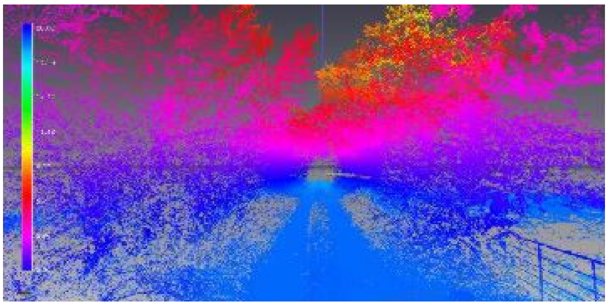


Figure 3.7. Three-dimensional scan along a 20-m section of roadside hedgerow showing heights represented by different colours.

The density of points can also be recorded for specific layers in the hedgerow, e.g. 1–2 m and 5–7 m height above ground level, and hence hedgerow structure can be accurately modelled. By utilising this TLS information at specific locations and for different hedgerow types, calibration techniques could be developed to greatly improve the biomass volume figures for larger LiDAR areas.

3.6.3 Tree detection

The higher sampling rate of TLS, compared with LiDAR, means that there is a finer resolution of objects being measured (Fig. 3.8). In addition, since the view

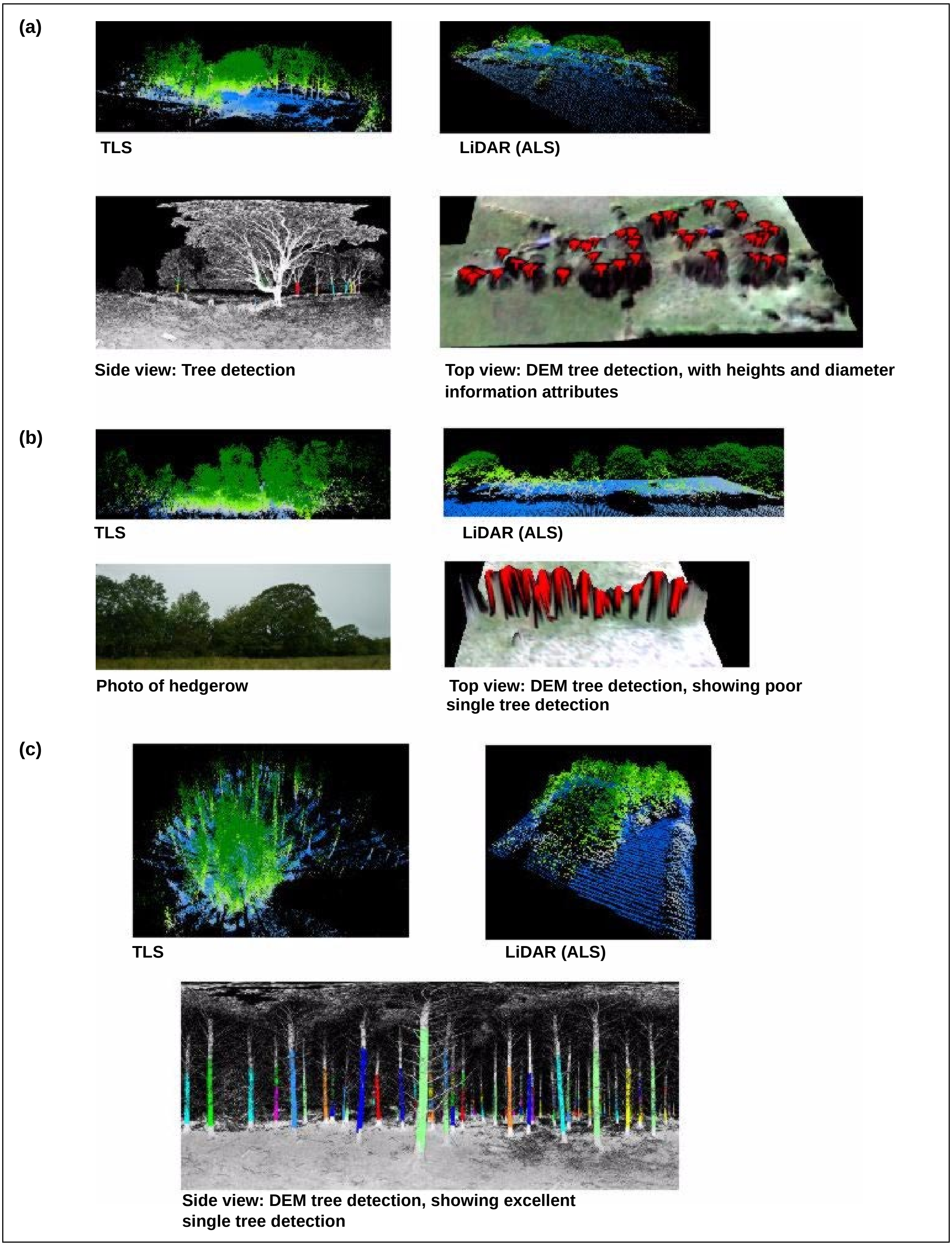


Figure 3.8. Terrestrial laser scanning (TLS), Light Detection And Ranging (LiDAR) and tree detection outputs for (a) a mature sycamore hedgerow, (b) a complex young hedge, and (c) a woodland patch. ALS, aerial laser scanning; DEM, digital elevation model.

angle for TLS is from ground level, detailed information on tree stems is obtained. In contrast, LiDAR provides better information on the crown characteristic because of a lower penetration and return of laser beams below the canopy.

The three examples in Fig. 3.8 show a comparison of LiDAR and TLS data and the detection limit of TLS algorithms to measure single tree information for mature, young hedgerows and woodland patches.

The TLS technology can clearly be used to derive biomass and volume for mature hedgerows, with distinct tree and woodland patches. However, TLS and processing cannot be used to detect trees in more complex or young hedgerows.

3.7 National Inventory Development

3.7.1 Optimisation of LiDAR sampling

Results show that sampling density can be reduced to 1 point/m^2, with no reduction in hedge/wall detection (Table 3.6), thus implying that the standard OSi survey methodology can detect but not necessarily measure hedges. This could reduce the cost of surveys and enable the use of existing OSi data sources in a national LULUCF reporting system for historical biomass assessments. The Z values for the 10 and 1-m return are very similar, suggesting that a 1-m return resolution is good enough for the detection of hedgerow features.

Although the detection resolutions of hedgerows are shown not to be influenced if the sampling frequency is reduced below seven returns/m^2, analysis of model

Table 3.6. Comparison of sampling intensity of seven and one laser returns/m^2. R is the total number of returns for selected hedgerow plots, R1 is the first return (a good indicator of height) and R2 is the second return (laser returns from the hedgerow crown at a lower height – good proxy of crown density). Z_{min}, Z_{max} and Z_{mean} are the statistics of laser height returns for the two sampling intensities. This provided an indication of the data distribution frequency of the two sample sets.

Seven returns/m^2						One return/m^2					
R	R1	R2	Z_{min}	Z_{max}	Z_{mean}	R	R1	R2	Z_{min}	Z_{max}	Z_{mean}
13,637	11,684	1,880	72	84	76	2,957	2,499	440	72	84	76
5,078	4,262	806	74	84	76	1,017	858	156	74	84	76
5,071	4,248	798	72	85	75	1,031	862	166	72	85	75
9,283	8,827	455	74	84	76	1,859	1,774	85	74	84	76
6,574	6,175	394	72	79	75	1,314	1,235	77	72	79	75
6,747	6,392	354	72	82	75	1,346	1,285	61	72	82	75
7,260	7,137	123	74	81	76	1,452	1,422	30	74	81	76
2,574	2,459	115	73	81	75	513	492	21	73	80	75
8,083	8,012	71	72	81	73	1,613	1,596	17	72	81	73
5,283	5,212	71	69	87	76	1,058	1,045	13	74	79	76
5,954	5,953	1	74	81	76	1,190	1,189	1	74	80	76
3,696	3,696	0	73	75	74	745	745	0	73	74	74
4,060	4,060	0	74	75	74	812	812	0	74	75	74
7,845	7,845	0	75	79	76	1,571	1,571	0	75	78	76
7,484	7,484	0	74	75	75	1,489	1,489	0	74	75	75
3,607	3,607	0	74	74	74	717	717	0	74	74	74
5,535	5,535	0	75	77	75	1,108	1,108	0	75	76	75

accuracy using the direct laser-metric estimate of biomass (see Table 3.6) shows that models are not robust at a sampling density of five returns/m^2. Based on these results, it is suggested that the minimum sampling density should not be less than five returns/m^2.

3.7.2 Inventory design

The guiding principles when designing a land-cover monitoring system can be summed up as:

- **Practicality:** Can the hedgerow classes proposed here be distinguished by remote sensing and GIS?
- **Utility:** Do the classes proposed here satisfy as the basis of a reporting scheme for current Environmental Protection Agency (EPA) needs, can it be adapted in the future if definitions change, and can the inventory provide useful information to agriculture?
- **Repeatability:** Can these classes form a basis of reporting – can we distinguish between classes and also meaningfully detect *change* on an annual basis?

The national and international experience outlined above provides a number of parameters within which to design a LiDAR inventory of the 3D physical characteristics of the national hedgerow stock. In general:

- The survey area should be between 0.6 and 1% of terrestrial area;
- Conventional LiDAR (3–7 points/m) survey is best in leaf-off;
- High-density or full wave form (FWF) LiDAR can be carried out leaf-on; and
- Geo-statistical clumping of sample areas is acceptable with a priori knowledge of distribution.

Good practice under the INSPIRE Directive and the present economic condition strongly suggest that the survey should be designed to meet multiple uses if possible.

3.7.2.1 *Size of survey area*

Ireland has a utilisable agricultural area (UAA) of 4 Mha or 40,000 km^2. Knowledge of where the hedgerows are can be gleaned from the Teagasc Hedgerow Map (see Fig. 3.9). Therefore, to take a 0.7% sample requires covering an area of 250 km^2.

In a conventional survey, this would imply 250 separate 1-km sample cells; however, this has cost implications (see Section 3.7.2.3). Covering fewer larger sample areas is cheaper. One possible option may be to take a pre-existing delineation of the landscape and use this as the basis for sampling.

Hydrological catchment maps provide an example of this sort of segmentation. The map in Fig. 3.10 shows all third-order catchments between 4 and 12 km^2 in size. The attraction of catchments is in the secondary utility of the LiDAR acquisition – LiDAR is most commonly acquired for creating DTMs for hydrological

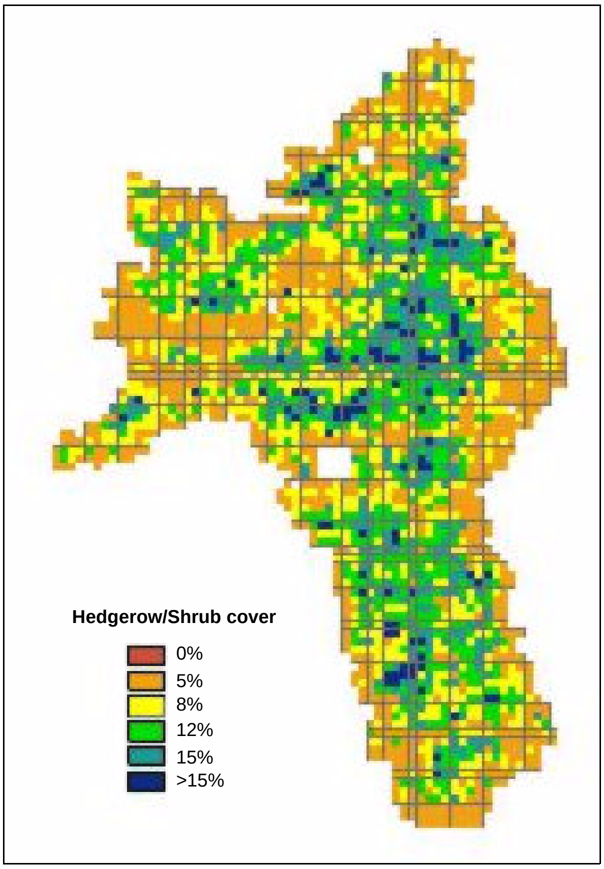


Figure 3.9. Hedgerow density (1 km^2) map for Co. Roscommon (produced by resampling of the THM05).

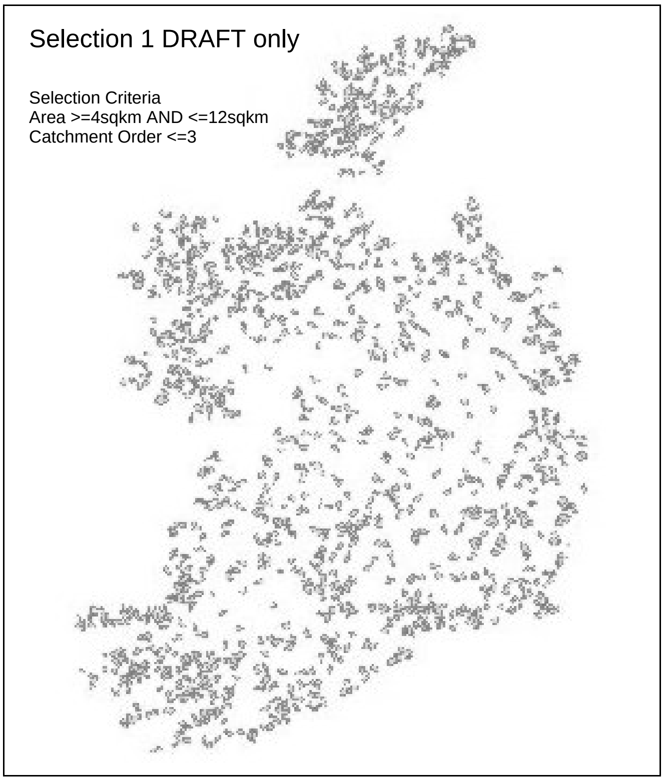


Figure 3.10. All third-order river catchments between 4 and 12 km^2 in size.

studies; however, these are only useful if they represent entire catchments. A selection of 40 of these catchments would satisfy Ireland's area requirement and if stratified against the distribution of hedgerows (low, medium high density) would satisfy the statistical requirements. The DTM created would be useful to many organisations.

However, as the basis for an ongoing system to monitor change, these areas are less attractive to co-funders. If the motivation were only to create a DTM, then co-funders would insist on the sample changing with each campaign so that a national DTM could be built up. Whilst a changing sample is satisfactory to calculate differences between campaigns and to record the total observed change, it cannot give actual change direction (are hedges growing wider and taller, or are there more hedges) – to do this a fixed, permanent sampling frame is needed.

The agencies with an interest in a fixed sampling frame are the Forest Service, the DAFM, the National Parks & Wildlife Service (NPWS) and the Department of the Environment, Community and Local Government. LiDAR when acquired with contemporaneous imagery (as is the case with most systems on offer) is an ideal tool for land-use and land-cover and habitat mapping and monitoring.

If the Forest Service NFI 2-km sampling framework were to be adopted, there are obvious reasons why the above agencies would be interested. As outlined in Section 3.7.2.3, the more areas that are surveyed and the more dispersed that they are, the higher the total cost of the survey; also, complex shapes can increase survey costs. A compromise is to use a 2-km by 1-km area as the LiDAR sample. The NFI intersect would be selected using a stratified random sampling basis (based on a hedgerow density from the THM).

Figure 3.11a shows an example of such a survey sample, while Fig. 3.11b shows the size of an individual sample plot.

3.7.2.2 Repeatability

It is important that any study is designed to coincide with the production cycle of the large European land-use projects in order to maximise benefit both nationally and internationally. LUCAS, CORINE and HRL (High Resolution Layers) are scheduled on a 3-

Figure 3.11. (a) Locations of 125 2-km × 1-km sample plots. (b) Example of an individual sample plot.

year/6-year cycle; therefore, the authors propose a 6-year cycle for hedgerow monitoring.

3.7.2.3 Cost analysis

The cost of a conventional field survey and data processing varies between €500 and €2,000 per square kilometre of survey – for this report, a median figure of €1,100/km^2 is used, based on published tender documents (Mayo County Council, 2007; Sligo County Council, 2008; Meath County Council, 2010).

In LiDAR survey campaigns, the costs depend on many factors:

- Mobilisation costs
  - Flying from base airport
  - Establishing GPS base stations
  - Weather
- Acquisition costs
  - Area
  - No targets
  - Weather
  - Sampling density
  - GPS quality
- Processing costs
  - Level required

- Sampling density.

A fixed cost per square kilometre is impossible to determine – it depends on the nature of the survey. No companies were asked to provide specific responses to what would have been non-existent contracts. However, comparison of existing tender documents, both in-house and international[6], suggest that the cost of the project outlined here would be approximately **€500–750/km^2** for acquisition and basic processing. Processing to construct a hedgerow map would cost more.

Assuming a processing schema was developed in a separate project, a running and checking algorithm within a project would be in the order of €100/km^2, making the operational cost of a survey of 250 km^2 approximately €150,000. This assumes that development costs have been covered in an earlier project. If the assumption is that the survey is carried out every 6 years, this gives an annual acquisition cost of €25,000 as a minimum.

The acquisition specifications used to make comparisons are:

- Low flown (min. 5 points/m^2);
- Multi-return pulse LiDAR;
- No base stations, corrections achieved with real-time kinematic positioning;
- 120 2-km^2 regular sites – acquisition period April to October;
- Data corrected to DTM, raw cloud data supplied; and
- Contemporaneous uncorrected colour Image acquisition.

There are many ways to reduce costs – having a wide window of acquisition allows the project to ‘piggyback’ on larger projects, thus covering mobilisation costs. Acquiring throughout the summer when it is generally cheaper, and clustering the targets around airports would also reduce costs.

The literature search in Section 1.2 showed that hedgerows can be characterised more easily in winter, in leaf-off conditions – this implies that sampling density can be reduced and, thus, the acquisition costs.

3.7.2.4 The ideal scenario

Ideally, one would reduce costs through share agreements with other governmental departments or institutions. Because other departments have a more general interest in land use and habitats, this may mean actually making the survey bigger – to cover 1% of the whole land mass, i.e. 600 km^2 or 300 sample sites to fully represent the State. Having a regular grid of sites and a larger contract should reduce the cost per square kilometre, possibly down to €400/km^2, with processing increasing due to multiple targets within the sample sites by possibly an extra €200/km^2. Thus, the cost of a full land-use/habitat survey data acquisition and processing for the State is €60,000/year.

3.8 Consultation with Stakeholders

A half-day workshop was held in Teagasc, Ashtown, for identified stakeholders, researchers and policy professionals in the areas of GHG inventory, biodiversity, landscape studies and agri-environment schemes. The aims of the workshop were to:

- Disseminate the research outputs;
- Make other institutions aware of the research applications; and
- Identify how to best incorporate all available resources into a national hedgerow carbon inventory.

The following persons were invited to attend: Frank Barrett (Forestry Service), Tom McHugh (ICON group), Thomas Harty (DAFM, LPIS), Gemma Weir (DAHG), Kevin Lydon (EPA), Neil Foulkes (Hedge Laying Association of Ireland), John Muldowney (DAFM), Stuart Green (Teagasc), Garret Mullooly (TreeMetrics), Alex Poveda (TreeMetrics), Phillip O'Brien (EPA), and Kevin Black (FERS).

6. A recent Scottish tender had a 260 km^2 area of forest to be surveyed, with very similar specification and desired outputs to those proposed here for a total cost of €63,000, or approximately €250/km^2. Obviously the scattered nature of this study’s survey mobilisation and equation increases costs.

Following a detailed presentation of the work carried out under the project, there was some feedback on the results presented and possible links with other organisations and individuals:

- County council surveys do not currently perform any assessments of biomass in hedgerows; some guidelines should be drawn up to facilitate this so that this information could be fed into a future inventory system as part of a ground-truthing validation exercise. There were numerous discussions on sampling strategies.

- It was generally agreed that simultaneous biomass and LiDAR assessments should be done on selected hedgerows to provide more robust and ground-truthed sequestration estimates. The influence of soil carbon stock changes should also be considered.

- Knowledge of the species composition of hedgerows in different areas or on different soil types would be useful because this would influence the sequestration potential and help with the design of a representative sampling strategy. Current LiDAR methods cannot distinguish species. There is, however, a new hedgerow survey database collated by Neil Foulkes (Hedge Laying Association of Ireland).

- There is a common interest with the DAFM with regards to farm payments and monitoring of hedgerows. In addition, the Forest Service would also be interested in assessing the use of LiDAR in its inventory. There may be good scope for governmental institutions and departments to share the costs for future LiDAR surveys. This would reduce data capture and processing costs.

- It was felt that the current assumption regarding the amount of carbon sequestered is realistic. However, the potential losses of hedgerow biomass due to management and the potential decrease in carbon sequestration in mature and degrading hedgerows should be considered. In particular, the potential of increasing carbon sequestration by management, such as hedgerow rejuvenation, should be considered. Although the proposed approaches will capture changes in sequestration due to increased areas of hedgerows and management, additional work is required to identify how certain management interventions may influence carbon sequestration potential.

4 Discussion and Conclusions

4.1 LiDAR and TLS Applications for Hedgerow Monitoring

The developed methodologies outlined in this study clearly demonstrate that LiDAR technology and sampling techniques can be applied to derive estimates of hedgerow biomass. Direct estimations of biomass using laser-metric statistics appear to provide the most robust and simplest way of assessing hedgerow biomass (Table 3.6). These findings are consistent with approaches used for forest inventories, where direct estimates based on laser-metric statistics are preferred (see Stephens et al., 2007). Stephens et al. (2007) suggested that a minimum sampling density for direct laser-metric assessment of forest biomass should be seven returns/m^2, which is similar to the results obtained in this study. Another advantage of using high-density sampling LiDAR surveys is that it may be easier to derive improved surface DEMs, which can be better for characterising ditches, walls or other structures that may interfere with the laser-metric assessment of hedgerow biomass. In this study, this problem was resolved by using a height cut-off for sampled laser points at 1.5 m. This would also exclude interference by non-woody biomass vegetation.

It should be acknowledged that the presented modelled estimates of hedgerow biomass require independent validation against ground-truthed assessments of hedgerow biomass. Ground measurements should be done in combination with LiDAR surveys of the same hedgerows at the same time. TLS technology could be used as a non-destructive measuring method of hedgerow biomass based on a smaller set of destructive biomass assessments. This component of the inventory development was outside the scope of this desk study.

Another required feature of the application of LiDAR for assessing the sequestration potential of hedgerows is that repeat surveys are required at a 5- to 10-year interval. Since this was outside the scope of the project, alternative approaches were applied. It is evident, however, that these approaches introduce a large degree of uncertainty and do not seem to be robust in some cases. For example, the steady-state assumption used by Henry et al. (2009) requires good information when establishing the time and maximum biomass values when carbon sequestration or biomass change is at steady state. Application of the IPCC good practice guidance default of a 50-year steady-state transition time and the 75th percentile of the hedgerow biomass distribution, as suggested by Henry et al. (2009), appears to overestimate the biomass carbon stock change when compared with alternative modelling approaches (see Section 3.4). This was, however, not the case when the same approach was adopted for non-forest woodland patches. This anomaly may be due to numerous factors, including:

- The frequency distribution of the hedgerow boundaries sampled for LiDAR estimation of biomass may have under-represented older, more mature, hedgerows as evident by the low mean hedgerow biomass per hectare, the skewed frequency distribution (i.e. suggesting a young age distribution) and the low frequency of high biomass values in the hedgerow sample (see Fig. 3.4a). This would have underestimated the steady-state biomass value used in the steady-state transition assumption, which results in an overestimation of hedgerow sequestration potential.

- The CARBWARE model used for estimating biomass gains and losses was developed for forests and not hedgerows. It is plausible that this could underestimate potential biomass stock changes.

- The estimates for non-forest woodland patches appear to be similar when both approaches are compared. This is because there is a better representation of the asymptote for biomass at the time of steady state and the more uniform biomass distribution of sampled woodland patches (see Fig. 3.5). This means that the application of the steady-state assumption would have yielded reasonable results when compared with the forest and woodland models used.

Despite these difficulties the estimated biomass sequestration rates of hedgerows in this study (0.66–3.3 t CO_2/ha/year) are higher than those reported for the UK (0.4–1.25 t CO_2/ha/year**)** by Falloon et al. (2004). However, the estimates in this study do not consider potential losses due to hedgerow management such as hedge cutting or removal. Adjustments to the estimated sequestration rates have been applied to the cost–benefit analysis (see Section 4.2) to account for these losses.

Estimates obtained for non-forest woodland patches are within the range of those reported for other Irish forests (Black et al., 2012) and for forest lands under reporting to the United Nations Framework Convention on Climate Change (UNFCCC) (Duffy et al., 2011).

Clearly the most robust approach for estimating biomass carbon stock changes in hedgerows should be based on repeat inventories using LiDAR and not simplified steady-state approaches unless more empirical information becomes available. However, the approaches used to estimate biomass stock using the direct laser-metric assessments are required when conducting the repeat LiDAR surveys/inventories. This approach would result in a more robust unbiased estimation of biomass carbon stock change, which would include losses, providing that the inventory sampling design is robust and represents all hedgerow types and management categories, as outlined in Sections 3.7 and 3.8.

TLS technology is currently used as a commercial inventory solution in the forestry industry. The demonstration study presented in Section 3.6 shows the potential application to hedgerow surveys. The approach has numerous advantages over LiDAR, including:

- A higher sampling resolution which can be used to better distinguish hedgerow features and develop tree detection and timber volume estimates. The tree detection algorithm appears to perform better than the LiDAR-based crown segmentation method. This may be due to the much higher sampling density of TLS versus LiDAR. However, in young and very dense hedgerow canopies, neither the TLS tree detection algorithms nor the LiDAR segmentation methods performed well.
- Because the scans are ground based, characteristics under the hedgerow canopy can be better defined. This provides the opportunity of accurately resolving structures that are not hedgerow features, such as walls and ditches.

The disadvantage of TLS approaches versus LiDAR is that this does not cover a large sample size and a large number of TLS plot scans may be required for a national inventory, thereby increasing the sampling cost. The potential application of TLS for hedgerow biomass inventories may be for developing non-destructive estimates of hedgerow biomass. This would initially be developed using TLS scans of hedgerow sections, followed by either allometric assessments of hedgerow biomass (i.e. using tree height or diameters as proxies of biomass), or by destructive sampling and direct measurement of biomass. Once robust TLS algorithms have been developed, these can be used as a ground-truthing technique to calibrate LiDAR estimates at a national scale. This is essentially a double-sampling technique using the higher resolution TLS to develop good biomass estimates, which are subsequently used to calibrate LiDAR models as presented in this study (Eqn 2.2a and Table 3.6).

4.2 Cost–Benefit Analysis

Assuming that the estimated sequestration potential for the pilot study area is fully representative of national hedgerows, the potential benefit in terms of carbon sequestration potential and revenue to the Exchequer is shown in Table 4.1. The cost–benefit analysis should be considered against numerous factors, particularly accounting rules, and current and future carbon dioxide prices.

4.2.1 The current Kyoto Protocol Article 3.4 accounting framework

A major consideration for assessing the potential cost–benefit of including hedgerows and woodland patches for accounting under Article 3.4 of the Kyoto Protocol

Table 4.1. A cost–benefit analysis showing the potential revenue returns, generated as tradable certified emission reduction (CER) units in the current EU trading scheme, against potential costs of a national inventory procedure.

Parameter		Value	Minimum	Maximum	Source
Above-ground biomass carbon sequestration potential ($t\ CO_2$/ha/year)	Hedgerows[1]	1.604	0.528	2.68	Section 3.4
	Non-forest woodland patches	2.55	2.24	2.86	Section 3.5
Total biomass carbon sequestration potential ($t\ CO_2$/ha/year)	Hedgerows[1]	1.9248	0.6336	3.216	IPCC GPG default shoot-to-root ratio
	Non-forest woodland patches	3.06	2.688	3.432	IPCC GPG default shoot-to-root ratio
National area	Hedgerows	272,360	252,300	292,430	Forest Service Ireland (2007a)
	Non-forest woodland patches	49,270	40,590	57,940	Forest Service Ireland (2007a)
Increase in area (ha) since 2000 (base year)	Hedgerows	4,000	3,200	4,800	Section 1.2.1.1[3]
	Non-forest woodland patches	493	394	591	Assume 1% increase
Total sequestration per year (Mt CO_2) in 2007	Hedgerows and non-forest patches	0.68	0.27	1.14	
Total sequestration per year (Mt CO_2) in 2000	Hedgerows and non-forest patches	0.67	0.27	1.12	
Net–net amount (t CO_2)		9,206.86	3,087.02	17,465.94	Accountable under Articles 7 and 8 of Kyoto Protocol
Carbon dioxide price (€/t CO_2)		€0.4	€0.4	€5	Current CER price (annual min. and max.)
Potential benefit net–net accounting (€/year)		€3,682.74	€1,234.81	€87,329.68	
Potential costs (€/year)[2]		€92,500.00	€80,000.00	€105,000.00	Section 3.7.2.4
Cost benefit		–€88,817.26	–€78,765.19	–€17,670.32	

[1]Adjusted for potential management losses, such as hedgerow cutting and removal, and for below-ground biomass (assume 20% increase).
[2]Includes additional €20,000 for national inventory compilation with quality assurance/quality control.
[3]Department of Agriculture, Food and Rural Development (2000) and Agricultural and Environment Structures (AES) Office, the follow-on scheme 10,000 km assume 4 m width.
IPCC GPG, Intergovernmental Panel on Climate Change Good Practice Guidance.

is the net–net accounting rule applied to these land-use categories. This means that the amount claimed is net of the emissions/removals in a selected base year (see Black et al., 2012). For this exercise, it is assumed that 2000 can be used as the base year because of information supplied by the DAFM on an increase in hedgerows of 10,000 km since the year 2000 (see Section 1.2.1.1). Assuming this applies to hedgerows with a minimum width of 4 m, this would equate to an area of 4,000 ha since 2000 (i.e. assumed between 2000 and 2007, see Table 4.1). Using adjusted carbon dioxide sequestration rates presented in Table 4.1, it can be expected that ~0.27–1.14 Mt CO_2 were sequestered in 2007 (only biomass). However, if the net–net accounting principle is applied using 2000 as the base year, this would only represent a net removal of 9,206–17,456 t CO_2/year (Table 4.1). Considering that REPS 4 has been discontinued, it is unlikely that the area of hedgerow could be expected to increase after 2010.

Based on this cost–benefit analysis and current carbon dioxide market prices, it is clear that there is no cost benefit under the current accounting rules (Table 4.1). This is primarily due to the small increase in hedgerow area since 2000, assuming that this information is correct. More work is required to accurately determine the change in hedgerow areas by comparison with a specific base year, which can be used as part of the NIR reporting and accounting framework.

4.2.2 Accounting and reporting beyond 2020

The precise modalities for accounting elected activities under Article 3.4 post-2020 are still not clear. It is likely that the accountable amount and modalities would depend on the magnitude of the burden-sharing target. If land-use activities were accounted on a gross–net basis, as is done for activities elected under Article 3.3, this would represent a net benefit to the Exchequer of 0.17–5.59 M€/year after costs for surveys, data processing and compilation of the NIR are included. The current gross–net accounting rules for forest management apply a cap, based on a negotiated maximum claimable amount. If a cap is applied to gross–net accounting for hedgerows, then the cap should be greater than the MRV costs to justify development of a national system or election of this activity under any future agreements.

4.2.3 Carbon dioxide price

The current carbon dioxide market price has decreased from €5 to €0.4 over the past year. This is primarily driven by a general reduction in country emission profiles as a result of the slowdown in the global economy. Therefore, most signatory countries to the Kyoto Protocol are likely to meet their reduction targets without needing to purchase certified emission reductions (CERs) or offsetting national emissions with Kyoto RMUs (such as Article 3.4 removals). This has in effect reduced the demand for CERs, exacerbated by the dumping of CERs onto the market. Current projections of future carbon dioxide market prices suggest that these are likely to increase as higher reduction targets are set and as new trading schemes in Australia and New Zealand come into play, but this may be anywhere from €1 to €5 (Delbosc et al., 2011) by 2020. Some predict a price of €5–12 by 2020 (Thomson Reuters (survey dated 4 April 2012))[7]. Using the current accounting net–net framework, the estimated increases in hedgerow area and annual costs of a national hedgerow carbon inventory would only return a cost benefit if the carbon dioxide market price exceeds €6/t CO_2.

4.3 Future of LiDAR

Most LiDAR estimates of biomass, both within and without forest, essentially use LiDAR to recreate the typical measurement made in the forest height, tree counts and diameter at breast height (DBH) through crown-shape proxies. More direct approaches employing statistical estimation of biomass using laser-metric variables have also been useful (Stephens al., 2007, Section 2.8).

A new generation of LiDAR measurements, exploiting the 3D nature of LiDAR, has led to biomass-volume estimates based on simple geometries (trees measured as cuboids, etc.). These new approaches further exploit the 'cloud' and segment the cloud into individual trees based on the 3D shape of a cloud segment. Rentsch et al. (2011) analysed woodland patches and tree lines with conventional LiDAR in leaf-off condition. The 3D segmentation of the tree line matched the ground observations, with an r^2 value of

7. http://www.cdcclimat.com/IMG/pdf/12-05_climate_brief_no13_-_supply_demand_for_cer_eru_in_the_ets.pdf

0.95, based on a small set of observations (n = 14). This work also compared conventional scanning with FWF LiDAR (equivalent to 100 points/m^2); this achieved similar accuracies only in leaf-on condition.

In a clever use of data fusion Chen and Hay (2011), combined object-oriented classification of QuickBird Imagery with contemporaneous LiDAR acquisition. Using machine learning tools and exploiting texture and shadow in the image, with a learning algorithm fed with a CHM derived from the LiDAR transect, they were able to create a pseudo-CHM over the entire QuickBird image based on the small LiDAR footprint sample. This is potentially a very useful tool to expand the effective area of a LiDAR survey for hedgerows as the structure of hedges makes them particularly amenable to extraction as objects.

Recent work in the UK has attempted to build a model that predicts the occurrence of hedgerows in the English landscape using other data sets (field boundaries, altitude, land cover, etc.). This proved to be successful; however, it is not needed in Ireland with the THM. Nevertheless, such a model could be developed for ‘risk’ on hedgerow removal to guide and focus site selection for the national land-use inventory.

4.3.1 Technological developments

The direction of LiDAR technology is toward smaller units deployed on new platforms with very high-density sampling and a degree of autonomy that reduces or eliminates the need for base stations of fixed targets to create 3D models accurately located in the real world.

- **FWF LiDAR:** As noted in this report, conventional LiDAR systems send out pulses of light and record multiple returns, the density of samples is determined by the distance of the scanner from the target and the scanning frequency of the system. Importantly, these systems only measure the time and intensity of the returned signals with FWF LiDAR (Mallet and Bretar, 2009) – the entirety of the signal is recorded allowing for the shape of the return pulse to be analysed as well as the recording of small returns that may fall below the detection threshold of conventional systems. This technology is already available and is being exploited within forestry (Jung, 2011).

- **UAV and LiDAR:** Mini-LiDAR units are in development that can be mounted on an unmanned aerial vehicle (UAV) platform (Lin et al., 2011). This technology, when mature, will offer the benefits of aerial laser scanning (ALS) and TLS, combined with very high sampling densities and potentially lower deployment costs. Current Irish Aviation Authority (IAA) guidelines would be comparable with using UAV at a 1-km tetrad scale.

- **TLS:** Technologies already exist for mobile scanning of objects without the need for a base station or fixed targets (cf. Google street mapping and the Maynooth University StratAG system). An interesting development is the Zebedee, a hand-held high-resolution scanner that can create 3D objects using recognition systems to build up common reference points as the user moves (Zlot et al., 2012). Already successfully used in archaeology, it has potential to become hugely beneficial in habitat field surveys, creating a 3D model of a hedge as quickly as you can walk along it.

- **Hyperspectral LiDAR:** An exciting medium-term development is the hyperspectral LiDAR system being developed in the Finnish Geodetic Institute. Conventional LiDAR uses one frequency of laser light, while the hyperspectral LiDAR system uses 20 across the whole spectrum, allowing for full fusion of 3D and hyperspectral techniques, thus showing structure and colour of vegetation and creating indices of the LiDAR returns to measure water stress disease (Hakala et al., 2012).

5 Observations and Recommendations

This study clearly demonstrates that the technology and methods exist to develop a national hedgerow inventory using LiDAR. This can be delivered at a low cost and may even be cost neutral depending on future land-based accounting frameworks and carbon dioxide market value. However, it is recommended that the following research and capacity development are required before a fully functional and IPCC Good Practice Guidance (GPG)-compliant inventory can be established:

- Direct measurements of hedgerow biomass are required to calibrate TLS or LiDAR-based assessments. The developed models in this study require independent validation to test the robustness of the approach. This information can also be used for uncertainty analysis, a key component of national inventory quality assurance/quality control.
  - To facilitate development of robust ground-truthing surveys, a cross-section of hedgerows representing all species, hedge types and management practices should be sampled in extensive field trials.
  - Ground-truthing field trials should be conducted together with limited and representative LiDAR and TLS surveys for robust model development.
- National institutions and departments should develop cohesive LiDAR survey, dissemination and inventory policies compatible with the INSPIRE Directive, so that the costs of acquiring and processing LiDAR data for multiple users can be reduced.
  - The national inventory design should incorporate current and future land-use observation systems, such as remote-sensing applications for land-use change (e.g. the Irish Land Mapping Observatory (ILMO) EPA project). Existing and future land-use observation systems should incorporate functionality to assess hedgerow area change over time. The land-use observation system should ensure that different land-use activities are consistently represented over time in accordance with the IPCC GPG and annexes to Decisions 15/CMP and 16/CMP.
  - Other LULUCF inventory, environmental and engineering applications, such as the national forest inventory, could share LiDAR data to maximise efficiency and reduce MRV costs.
- Heritage Council and county council surveys of hedgerows should develop a method to assess the biomass of hedgerows. The future inventory should use available hedgerow databases as additional activity data for the national carbon inventory.
- If the modalities of the current Kyoto Protocol LULUCF accounting frameworks do not change after 2020, a baseline study is required to determine a reference level for net–net accounting for cropland and grazing land management.
  - Under the current framework, the reference level base year is 1990, but this may change under the ongoing Conference of the Parties (COP) negotiations. Selection and negotiation of a suitable reference year should be based on available resources and the historic information required to develop baseline reference levels.
  - Systems need to be developed to include all carbon pools, such as below-ground biomass, dead organic matter and soil carbon stock change, to ensure completeness of the inventory in accordance with IPCC GPG and annexes to Decisions 15/CMP and 16/CMP.
- Environmental and agricultural policy and practice should be developed to maximise climate change mitigation potential in the Irish

landscape, but not at the cost of other environmental services or agricultural management objectives. For example, the sequestration potential of hedgerows could be maximised by management practices, such as hedgerow rejuvenation or coppicing and establishment of new hedgerow, whilst still maintaining biodiversity and agricultural objectives.

6 Project Outputs

Papers Presented at Seminars

Black, K., Poveda, A., Mullooly, G. and Green, S., 2012. Towards a national biomass and greenhouse gas inventory for hedgerows using high density return LiDAR. *6th Annual Irish Earth Observation Symposium*. 1–2 November 2012, Dublin Institute of Technology, Dublin, Ireland.

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Acronyms

AES	Agricultural and Environmental Structures
ALS	Aerial laser scanning
C	Carbon
CER	Certified emission reduction
CHM	Canopy height model
COP	Conference of the Parties
CS	Countryside survey
DAFM	Department of Agriculture, Food and the Marine
DBH	Diameter at breast height
DEFRA	Department for Environment, Food & Rural Affairs
DEM.	Digital elevation model
DTM	Digital terrain models
EPA	Environmental Protection Agency
EU	European Union
FIPS	Forest Inventory and Planning System
FWF	Full wave form
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse gas
GIS	Geographic information systems
GPG	Good Practice Guidance
GPS	Global positioning system
HRL	High Resolution Layers
HWS	Hedgerow, woodland and scrub
IAA	Irish Aviation Authority
ILMO	Irish Land Mapping Observatory
INSPIRE	Infrastructure for Spatial Information in Europe
IPCC	Intergovernmental Panel on Climate Change
k-NN	k-Nearest Neighbour
LiDAR	Light Detection And Ranging
LUCAS	Land Use/Cover Area Frame Statistical Survey
LULUCF	Land use, land-use change and forestry sector
MRV	Monitoring, reporting and verification

NIR	National Inventory Report
NIWT	National Inventory of Woodland and Trees
NPWS	National Parks & Wildlife Service
OSi	Ordnance Survey Ireland
QA	Quality assurance
QC	Quality control
REPS	Rural Environment Protection Scheme
RMSE	Root mean squared error
RMUs	Removal units
THM	Teagasc Hedge Map
TLS	Terrestrial laser scanning
UAA	Utilisable agricultural area
UAV	Unmanned aerial vehicle
UNFCCC	United Nations Framework Convention on Climate Change

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail;
- scardadh dramhuisce;
- dumpáil mara.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments.
The programme is structured according to four linked thematic areas with a strong cross cutting emphasis.
Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see
www.epa.ie/whatwedo/climate/climatechangeresearch

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