Report No.454

Farm-Carbon: Hedgerows and Non-forest Woodland (Hedgerow Carbon Project)

Authors: Lilian O'Sullivan, Gary Lanigan, Daire Ó hUallacháin, Shiva Rahimi-Tanha and Kevin Black

www.epa.ie

Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

- Large-scale industrial, waste and petrol storage activities;
- Urban waste water discharges;
- The contained use and controlled release of Genetically Modified Organisms;
- Sources of ionising radiation;
- Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

National Environmental Enforcement

- Audit and inspection of EPA licensed facilities;
- Drive the implementation of best practice in regulated activities and facilities;
- Oversee local authority responsibilities for environmental protection;
- Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
- Assess and report on public and private drinking water quality;
- Coordinate a network of public service organisations to support action against environmental crime;
- Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment

- Implement and enforce waste regulations including national enforcement issues;
- Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
- Develop and implement the National Waste Prevention Programme;
- Implement and report on legislation on the control of chemicals in the environment.

Water Management

- Engage with national and regional governance and operational structures to implement the Water Framework Directive;
- Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change

- Publish Ireland's greenhouse gas emission inventories and projections;
- Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
- Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment

- Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
- Produce the State of Ireland's Environment and Indicator Reports;
- Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
- Oversee the implementation of the Environmental Noise Directive;
- Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development

- Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
- Collaborate with national and EU environmental research activity.

Radiological Protection

- Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
- Assist in developing national plans for emergencies arising from nuclear accidents;
- Monitor developments abroad relating to nuclear installations and radiological safety;
- Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information

- Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
- Promote the link between health and wellbeing, the economy and a clean environment;
- Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
- Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

- Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

epa Research

Farm-Carbon: Hedgerows and Non-forest Woodland (Hedgerow Carbon Project)

Authors: Lilian O’Sullivan, Gary Lanigan, Daire Ó hUallacháin, Shiva Rahimi-Tanha and Kevin Black.

Identifying pressures

The EU aims to be climate neutral by 2050. Central to this ambition is land management that supports carbon sequestration, and enhancement of carbon sinks or the reversal of their emissions. Current national greenhouse gas emission inventory submissions to the United Nations Framework Convention on Climate Change show that the land use, land use change and forestry (LULUCF) sector is a net source of emissions in Ireland. However, emissions and removals are not currently disaggregated in national emission inventory estimates.

In previous research, hedgerows have been recognised as playing an important role in sequestering carbon, storing it in woody growth, roots, leaf litter and soil organic matter beneath the ground. In Ireland, hedgerows are an important perennial landscape feature, estimated to cover 689,000 km. To enable the estimation of the emissions and removal potential of hedgerows, assessments of carbon stock changes over time are needed. This would facilitate the inclusion of reporting of hedgerow removals and emissions in inventory submissions. However, accurate estimations of biomass have traditionally been difficult to establish.

The aim of this research is therefore to advance understanding of the contribution of hedgerows and non-forest woodland (NFW) patches to carbon stocks in agricultural landscapes.

Informing policy

Ireland has committed to a series of international climate commitments that aim to address the impact of anthropogenic activities on the climate system. Collectively, these commitments endorse the important role of land-based activities in the mitigation of climate change. Delivering on climate ambitions envisages land use and management targeted towards the enhancement of carbon sinks, including the reversal of decreasing sinks.

Across the EU as a whole, the LULUCF sector represents a carbon sink, removing more carbon than it has emitted every year since 1990. In contrast, the Irish LULUCF sector has been a source of emissions every year from 1990 to 2020. Meeting emission reduction targets in this sector is set to become even more challenging, as the size of the national forest sink is reducing as a result of increased harvesting and reduced replanting.

In Ireland, hedgerows have been identified as an area with the potential to enhance terrestrial carbon sequestration. The capability to estimate and report greenhouse gas emissions/removals could inform hedgerow management actions in favour of enhancing their sink potential for climate change mitigation, thus assisting Ireland in meeting international climate commitments.

Developing solutions

Currently, hedgerows/NFW are not explicitly accounted for in national inventory reports. This report addresses this knowledge gap to better account for hedgerows/NFW by measuring their land use effects (data on single trees is already known) on carbon sequestration and stocks, including above- and belowground biomass and soil organic carbon measurements.

To achieve this, biomass measurements estimated using ground-truth drone approaches were compared with actual biomass data. Widely used process-based carbon models utilising measured data were compared for suitability for scaling potential. To assess the impact of hedgerows on farming systems, the modelled hedgerow inputs and outputs were applied to the “average” dairy, beef and arable farming systems in Ireland. This analysis highlights how the retention and planting of new hedgerows has important mitigation potential at farm scale. Finally, a decision support tool in the form of an integrated scorecard that incorporates both carbon sequestration and biodiversity indicators was produced, for use in local assessments.

EPA RESEARCH PROGRAMME 2014–2020

Farm-Carbon: Hedgerows and Non-forest Woodland (Hedgerow Carbon Project)

(2019-CCRP-MS.64)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Teagasc and Forest Environment Research and Services Ltd

Authors:

Lilian O'Sullivan, Gary Lanigan, Daire Ó hUallacháin, Shiva Rahimi-Tanha and Kevin Black

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research. This project has been co-funded by the Department of Agriculture, Food and the Marine (DAFM).

The authors would like to acknowledge the members of the project steering committee, namely Bernard Hyde (EPA), Brian Readi (DHPCLG), Phillip O'Brien (EPA), Niall Ryan (DAFM), Philip Blackwell (DAFM), John Redmond (DAFM), Barry O'Donoghue (NPWS) and Paul Burgess (Cranfield University), and Georgia Bayliss-Brown, Rachel Clarke, Karen Roche and Hannah Linehan (Research Project Managers on behalf of the EPA).

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. The Environmental Protection Agency, the authors and the steering committee members do not accept any responsibility whatsoever for loss or damage occasioned, or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

This report is based on research carried out/data from April 2020 to September 2022. More recent data may have become available since the research was completed.

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

EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-158-0 March 2024

Price: Free Online version

Project Partners

Lilian O'Sullivan
Teagasc
Environment, Soils and Land Use Department
Johnstown Castle
Co. Wexford
Ireland
Y35 TC97
Email: Lilian.OSullivan@teagasc.ie

Gary Lanigan
Teagasc
Environment, Soils and Land Use Department
Johnstown Castle
Co. Wexford
Ireland
Y35 TC97
Email: Gary.Lanigan@teagasc.ie

Daire Ó hUallacháin
Teagasc
Environment, Soils and Land Use Department
Johnstown Castle
Co. Wexford
Ireland
Y35 TC97
Email: Daire.OHuallachain@teagasc.ie

Kevin Black
Forest Environment Research and Services Ltd
Navan
Co. Meath
Ireland
Email: Kevin.Black@fers.ie

Contents

Acknowledgements **ii**

Disclaimer **ii**

Project Partners **iii**

List of Figures **vii**

List of Tables **viii**

Executive Summary **ix**

1 Hedgerows and Greenhouse Gas Fluxes **1**

1.1 Policy Impetus 1

1.2 Previous Research 2

1.3 The Challenge 2

1.4 Aims and Objectives 3

2 Hedgerow Assessments and Biomass Modelling **5**

2.1 Site Selection 5

2.2 Description of Field Sampling and Laboratory Analysis 5

2.3 Description of the Unmanned Air Vehicle Survey 7

2.4 Biomass to Volume Conversion Factor Development Using Regression Equations 8

2.5 Hedgerow Biomass Carbon Results 8

2.6 Biomass Models and Equations for Volume to Biomass Conversion 8

3 Scaling Up: Estimating Carbon Stock Changes **11**

3.1 Scaling to Estimates at County Level 11

3.2 Results of Scaled Estimates 13

3.3 Conclusions from Scaling Study 14

4 Modelling Soil Organic Carbon **15**

4.1 Comparison of Process-based Models for Soil Organic Carbon 15

4.2 Process-based Model Results 15

4.3 Conclusions from Process-based Modelling of Soil Organic Carbon 18

5 Impact of Hedgerows on Farm-scale Emissions 20

5.1 Farm-level Assessment 20

5.2 Opportunity of Hedgerows for Reducing Farm-scale Emissions 20

5.3 Conclusions 21

6 Integrated Scorecard Development 23

6.1 Approach 23

6.2 Existing Scorecard Review 24

6.3 Development of an Integrated Scorecard 25

7 Conclusions and Recommendations 27

7.1 Biomass Modelling and National Inventory Reporting 27

7.2 Soil Organic Carbon Modelling 27

7.3 Farm-scale Opportunity 27

7.4 Integrated Scorecard 28

7.5 Future Recommendations 28

References 30

Abbreviations 34

Appendix 1 List of Equations 35

Appendix 2 Set-up of the YASSO and RothC Models 38

Appendix 3 Limitations 39

List of Figures

Figure 2.1. One zone of five at each of the eight sites 6

Figure 2.2. Biomass pools and custom equipment 7

Figure 2.3. Custom-built air-spade to clean root biomass in-field and samples being processed 7

Figure 2.4. Regression analysis showing the fitted relationship between hedgerow AGB and hedge PV (a) and adjusted (Adj.) PV (c) for the two hedge types. Model residuals vs predicted hedge biomasss values are shown for model A (b) and model B (d) 9

Figure 3.1. NFI grid points identified as hedgerows and biomass sample sites (red crosses) 11

Figure 3.2. Aerial images (top panels) showing plot (plot 12) centre location, plot areas and hedgerow sample areas in 2015 (left) and 2019 (right). The middle panels show the DEM of the hedgerow area in 2015 and 2019 12

Figure 3.3. Box and whisker plot for biomass CSCs for different management (cut back, emergent, removed and unmanaged) and hedge profile (I, irregular; R, regular) types 13

Figure 4.1. DOM inputs (top panels) and cumulative DOM C fluxes (bottom panels) for regular (a) and irregular (b) hedges over a 50-year period 15

Figure 4.2. Measured annualised (observed ΔSOC, open circles) and modelled ΔSOC using YASSO (black circles) and RothC (grey triangles) stock changes across the irregular (a) and regular hedge (b) chronosequences 17

Figure 4.3. Modelled AGB, BGB and DOM stocks (top panels), and stock changes and NEE (bottom panels) of regular (left panels) and irregular hedgerows (right panels) over a 50-year time period 18

Figure 5.1. GHG emissions expressed on a per hectare and per farm basis 21

Figure 6.1. Integrated scorecard weighted to account for both biodiversity and C metrics 26

List of Tables

Table 2.1. Overview of selected sites according to age and management intensity 5

Table 2.2. Overview of key data from sample plots (*n* = 40) 8

Table 2.3. Model performance for models A and B and different hedgerow types, regular managed (R) and irregular (I) 10

Table 3.1. Representative area and mean AGB, BGB C stocks and total biomass CSC for different hedgerow profile and management categories 13

Table 3.2. Estimated changes in hedgerow area, AGB and BGB stocks, total biomass CSC and mean biomass CSC for the total, remaining, removed and emergent hedgerows over the period 2015–2019 14

Table 4.1. Chronosequence site information, SOC stocks for paired plots with different land uses and inferred SOC stock changes (ΔC) 16

Table 5.1. Activity data for the average dairy, beef and arable farm 20

Table 5.2. CO_2 potential equivalent C and CO_2e expressed per hectare per year for biomass, SOC and combined CO_2 for biomass SOC 21

Table 5.3. Farm system emissions equivalent associated with hedgerow management 22

Table 6.1. Projects with scorecards relating to hedgerow quality, and hedgerow structural variables likely to influence C storage and sequestration 23

Table 6.2. Hedgerows assessed based on six existing scoring systems: site codes, type and age, based on Table 2.1 site characterisation data 24

Table A1.1. Solved parameters for AGB, BGB and hedgerow width (equation A1.1) 36

Table A1.2. Solved parameters for litter proportion (*Pl*, equation A1.13) and deadwood proportion (*PBC*, equation A1.16) 37

Table A3.1. List of limitations indicated for each site in relation to existing scorecard models 39

Executive Summary

The EU aims to be climate neutral by 2050. Land management that supports carbon sequestration and enhancement of carbon sinks or the reversal of carbon sink emissions is central to this ambition. Current national greenhouse gas emission inventory submissions to the United Nations Framework Convention on Climate Change show that the land use, land use change and forestry (LULUCF) sector is a net source of emissions in Ireland. Hedgerows are a perennial landscape feature across Ireland, estimated to cover 689,000 km, and these have previously been suggested to be a carbon sink. To enable the assessment of the emissions and removal potential of hedgerows, assessments of carbon stock changes (CSCs) over time are needed, so that reporting of hedgerow removals and emissions can be included in the national emission inventory estimates.

To assess CSCs, direct measurements of hedgerow biomass are required to calibrate previously tested remote measurement techniques. A field survey was completed to collect empirical data on hedgerows to establish the relationship between measured hedgerow biomass and corresponding measurements of hedgerows surveyed remotely. A cross-section of representative hedgerows were surveyed, selected to represent different management intensity and age ranges. The aboveground and belowground biomass was directly quantified and dry matter analysed for carbon. An unmanned air vehicle survey to calculate projected aboveground biomass volumes at selected sites was also completed. Cross-section profiles of hedgerows were generated and two main sub-classes were defined: (1) narrow, regular-shaped, intensively managed hedgerows and (2) irregular, wider, less intensively managed hedgerows. For these two hedgerow types, two statistically significant aboveground models with solved coefficients were developed. A single belowground biomass model was also generated.

A scaled-up sampling approach was applied to two counties, using repeated aircraft survey data to assess biomass CSCs over time. The highest increase in mean biomass CSC was found for emergent (recently planted) hedgerows ($3.69\,\mathrm{tC\,ha^{-1}\,y^{-1}}$) followed by unmanaged irregular hedgerows ($2.87\,\mathrm{tC\,ha^{-1}\,y^{-1}}$). The largest biomass losses occurred when irregular hedgerows were permanently removed. In the period 2015–2019, hedgerow management resulted in net emissions, even with significant net carbon increases in unmanaged hedgerows.

The suitability of the YASSO and Rothamsted soil carbon (RothC) models was validated against measured soil organic carbon (SOC) changes inferred from measurements from land use change paired plots. Measured SOC accumulation was shown to decline with hedgerow age. The analysis confirmed that irregular hedgerows have a higher sequestration potential; however, management strategies are required to sustain carbon stocks in older and more intensively managed hedgerows. It is recommended that tier 2 SOC factors developed in this study should be applied in national emission inventory estimates. However, a more intensive soil sampling programme is necessary to develop more robust tier 2 SOC factors. A major finding is that the long-term carbon sequestration of hedgerows may be overestimated. More effort is required to develop models of SOC dynamics specific to hedgerow systems.

To assess the impact of hedgerows on farming systems, the modelled hedgerow inputs and outputs were applied to the “average” dairy, beef and arable farming systems in Ireland. Data from the National Farm Survey were applied to characterise the main farming systems in Ireland, including averages of greenhouse gas emissions, farm activity and hedgerow area. The potential emission savings opportunity associated with the planting of additional hedgerows or reducing the management intensity of hedgerows was estimated.

Lastly, a review of existing biodiversity scorecards indicated that current scorecards used in hedgerow assessments overlook the carbon benefit of hedgerows. This research proposes an integrated scorecard combining biodiversity and carbon indicators.

In conclusion, methods to report hedgerow CSCs have now been developed for the Irish LULUCF inventory. Although the research indicates that current management of hedgerows may result in net emissions from the biomass pool, alternative, less intensive, hedgerow management can result in significant removals of carbon dioxide within the LULUCF sector. Policy incentives to allow less intensive management of existing hedges, establishment of new hedges and regeneration of older hedges would increase both their carbon sequestration and biodiversity ecosystem service potential.

1 Hedgerows and Greenhouse Gas Fluxes

1.1 Policy Impetus

Ireland has signed up to a series of commitments that aim to address the impact of anthropogenic activities on the climate system, including the United Nations Framework Convention on Climate Change (UNFCCC). Parties to the UNFCCC are obliged to submit a National Inventory Report of greenhouse gas (GHG) emissions and removals annually, detailing the procedures and calculations used in its compilation. The Kyoto Protocol (under the UNFCCC) commits parties to internationally binding emission reduction targets, including the accounting of emissions and removals related to land use, land use change and forestry (LULUCF) (regulated under Articles 3.3 and 3.4 of the Protocol (UNFCCC, 2014)). Other climate commitments include those related to the Sustainable Development Goals adopted in 2015 (UN, 2016) and the Paris Agreement Article 4(1), which entered into force in 2016 (EC, 2016a, b). The Paris Agreement (adopted in 2015) represents the first universal, legally binding global climate change agreement (EC, 2016a, b). As part of this agreement, "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" is a long-term goal, highlighting the importance of land use and forests in reaching the long-term mitigation objectives (UNFCCC, 2016:4). Within Europe, the EU LULUCF Regulation determines the rules going forward (EU, 2021). This regulation includes a "no debit" rule, which means that Member State emissions accrued from land use have to be entirely compensated for by an equivalent removal of carbon dioxide (CO_2) from the atmosphere through sector actions in the 2021–2030 period (EU, 2021). Concurrently, the European Green Deal and the EU Biodiversity Strategy for 2030 include a 10% target for high-diversity farmland and potential farmer income from carbon (C) sequestration (EC, 2019). This signals a policy shift in favour of land management that optimises the sink potential of the land but also the potential synergies between climate and biodiversity strategies. Collectively, these commitments endorse the important role of land-based activities in the mitigation of climate change.

Delivering on climate ambitions envisages land use and management targeted towards the enhancement of C sinks, including the reversal of decreasing C sinks (EC, 2022). Global GHG sources and sinks from agriculture, forestry and other land use amount to ~10 $GtCO_2$ and –2 $GtCO_2$ annually (FAO, 2014). Land use and land use change impact the terrestrial biotic and soil C pool, with agricultural management having reduced soil C pools in particular (Batjes, 1996; Lal, 2004). Although the LULUCF sector has been a sink across the EU since 1990, the Irish LULUCF sector has been a source of emissions every year from 1990 to 2020, primarily due to emissions associated with drained organic soils (Paul *et al.*, 2018; GoI, 2022). Meeting emission reduction targets in this sector is set to become more challenging for Ireland, as the size of the national forest sink is reducing, with low (re)planting rates and the sequestration potential of forestry on organic soils having previously been overestimated (Jovani-Sancho, 2021; GoI, 2022). Wood harvests are projected to almost double, as Irish forests have the potential to increase the supply of round wood from 4 million m^3 per year to over 7.9 million m^3 per year by 2035 (COFORD, 2021). Augmenting sinks by enhancing removals of atmospheric CO_2 through improved management is one pathway for GHG mitigation (IPCC, 2001; Smith *et al.*, 2008; Lanigan *et al.*, 2018). In Ireland, hedgerows are a prominent landscape feature with the potential to enhance terrestrial C sequestration (Black *et al.*, 2014a). In agricultural landscapes, hedgerows can be defined as linear structures composed of shrubs and trees, established on agricultural field borders/boundaries. Action to improve the management of hedgerows requires capability to estimate and report GHG emissions/removals. At an applied level, this could inform hedgerow management actions in favour of enhancing their sink potential for climate change mitigation, e.g. UK research shows that extending their width has greater potential to sequester C into aboveground biomass (AGB) than extending their height (Axe *et al.*, 2017). Historically, under the Basic Payment Scheme cross-compliance obligations, farmers have been incentivised to maintain hedgerow width to less than 4 m to limit encroachment to avoid a payment penalty (DAFM, 2020).

1.2 Previous Research

Hedgerows store C in the wood and leaves above ground and also in the soil below in the hedgerow roots and through decomposition of the leaf litter that falls from the hedge. The dry matter (DM) of wood biomass for broadleaved species in the northern hemisphere is reported at 46–52% (Matthews, 1993), with the woody content of hawthorn and blackthorn, the most commonly found species in Irish hedgerows (e.g. Foulkes, 2007), containing on average 48.3% C (Axe, 2015). Axe (2015) found limited difference in species level analysis for overall C stocks. A meta-study of hedgerows found that soil organic carbon (SOC) under hedgerows was ~32% higher than in adjacent cropland, but no significant difference was found when adjacent to grassland soils (Drexler *et al.*, 2021).

Knowledge on the quantity of hedgerow biomass at the national scale is required to estimate the carbon stocks. Accurate estimations of biomass have traditionally been difficult to establish. However, new technologies have emerged and have been assessed for their suitability to support these estimations. The Teagasc Hedge Map indicated that an estimated 482,000 ha or 6% of the country was recorded as hedgerow or scrub (non-forest trees and woody plants), with up to 12% cover in County Monaghan (Green, 2011). Green *et al.* (2019) found a decline in total hedgerow length, ranging from a 0.16% to 0.30% decline per annum, in the years 1995, 2002 and 2015. A re-survey of the 2010 County Monaghan hedges showed a higher annual removal rate of 0.9%, of which 75% was attributable to agriculture (Mac Elwain *et al.*, 2021). Remote technologies, including terrestrial laser scanning (TLS) and airborne light detection and ranging (LiDAR), were found to be suitable for biomass estimation (Black *et al.*, 2014a). However, the use of imaging radar was found to be unsuited to deriving hedgerow biomass directly from radar backscatter (Green *et al.*, 2019).

Historically, hedgerow surveys in Ireland, including the 21 county or sub-county surveys led by the county councils and supported by The Heritage Council (see, for example, Aulino Wann & Associates, 2009), have concentrated on biodiversity. Importantly, several metrics that are relevant for biodiversity have relevance in terms of C stocks and sequestration. Structural characteristics such as height and width or continuity factors such as gappiness that provide insight into biomass density in the hedgerows are some examples. Larkin (2019) assessed hedgerows on 92 intensively managed farms and found that 90% were classed as low quality, with only 1% being of high quality. These studies highlight scope to enhance hedgerows for climate and biodiversity outcomes simultaneously; however, the national sink potential of hedgerows may be in decline.

1.3 The Challenge

The total C stock of any terrestrial ecosystem is represented by the sum of C in the living and dead biomass and in the soil C pools. These C pools are relevant to assess the emissions or removals of CO_2 from LULUCF (IPCC, 2006). To include hedgerows in inventory reporting, it is necessary to know the extent of hedgerows, the size of hedgerows (width and height) and the type of management. Knowledge of the typical amount of C stored in Irish hedgerows is also required. However, the complex structure of hedgerows and their high variability in terms of structure and management (impacting C stock accumulation over time) makes hedgerows challenging to measure (Drexler *et al.*, 2021).

In this work, we define hedgerow width of up to 20 m, but this is based on the top view, which includes the tree crown width. By definition, hedgerows do not meet the criteria for inclusion in the Intergovernmental Panel on Climate Change (IPCC) forestry land use accounting category (must be > 20 m width), thereby overlooking potentially the largest element of the Irish arboreal landscape (Black *et al.*, 2014a). Within Europe, Denmark is the only country to include hedgerow biomass C stock change (CSC) estimates in its National Inventory Report and annual GHG submissions to the UNFCCC and the European Commission (Nielsen *et al.*, 2021). Hedgerows in Ireland are contained within the land use definitions outlined for croplands and grasslands in Ireland's annual GHG submissions to the UNFCCC and the European Commission. To optimise the climate mitigation potential of hedgerows, more explicit accounting that can assess CSC is required. However, a wide range of uncertainty exists in relation to the rate of C accumulation and storage in hedgerow biomass and soils, the extent of management and removals, and the effect of age and soil depth on CO_2 sequestration (Ford *et al*., 2019; Viaud and Kunnemann, 2021; Biffi *et al*., 2022).

Overall, the National Inventory Report indicates that issues remain with respect to a time series in terms of the extent and condition of non-forest woody biomass along with methodological issues in mapping their change over time (Duffy *et al*., 2022).

There are currently no model frameworks or empirical data to quantify changes in net ecosystem exchange (NEE) of hedgerows over time or in relation to management intensity. However, the principles used to develop forest ecosystem models such as YASSO (Liski *et al*., 2005) or CBM-CFS3 (Kurz *et al*., 2009) can be applied to hedgerow systems if biomass inputs and turnover rates between dissolved organic matter (DOM) in the C pool are characterised. The turnover of C between chemical pools within the DOM pool (i.e. deadwood, litter and soils) can be simulated in the YASSO model. The model has been parameterised for brown earths, lithosol, podzols and gley soils for Irish forest systems in Ireland, and this has been demonstrated to robustly estimate SOC and DOM stock changes for afforested ecosystems on mineral soils (Black *et al*., 2014b). The factors governing DOM and SOC accumulation in forests are likely to be quite similar to those processes in hedgerows. However, in contrast to forest ecosystems, there is little information on the key driving factors influencing DOM pool fluxes in hedgerows, particularly litter inputs and deadwood inputs due to hedge cutting. The Rothamsted soil carbon (RothC) model has been used to model SOC dynamics in a variety of ecosystems (Jenkinson, 1999) and models the turnover of organic C in non-waterlogged topsoils to calculate the total organic C. RothC similarly divides SOC into a number of conceptual C pools, with each pool defined by its lability. The model splits soil C input into decomposable plant material (DPM) and resistant plant material (RPM), with the ratio depending on the origin of the plant materials. DPM and RPM decompose at different rates into microbial biomass (BIO) and humus (HUM), thereby releasing CO_2 (Coleman and Jenkinson, 1999). BIO and HUM then decompose at different rates, producing more CO_2, BIO and HUM. The partitioning of the products of the decomposition depends on the soil clay content, whereas decomposition rates are modified by temperature, soil moisture and cover vegetation. The suitability of these two widely used models is assessed within this project.

The chronosequence approach has been widely used to characterise NEE across forest age profiles (e.g. Black *et al*., 2009); however, the assumption is that all sites have the same site, climate and management characteristics. Such models have not been tested for estimating the NEE of hedgerows.

This approach is based on one measurement point in time across a range of sites varying in age since forest establishment. In this study, we used both the YASSO model and the RothC model to assess the impacts on SOC. We applied both models to hedgerows using data chosen from a series of sites selected across a chronosequence varying from 13 years to more than 50 years post hedge establishment.

1.4 Aims and Objectives

This work aims to advance capacity to incorporate hedgerows into annual GHG emission and removal estimates reported to the UNFCCC and the European Commission. Furthermore, the study aims to review and optimise scorecards with a view to developing an integrated scorecard to rapidly assess the quality of hedgerows with respect to C management and biodiversity (e.g. as part of results-based payment approaches). Few studies have related aerial imagery to measured biomass and related changes in biomass to hedgerow management. The primary objective of this research was to collect empirical data on hedgerows so that relationships between measured hedgerow biomass and remotely captured volume measurements could be developed. This builds on the recommendations by Black *et al*. (2014a), who pointed to the need for direct measurements of hedgerow biomass to calibrate remote measurements with a cross-section of hedgerows to represent the main hedge types and management practices. The overall approach was to estimate hedge biomass stock changes based on remote assessments of hedgerow projected volume (PV) (Green *et al*., 2019; Levin *et al*., 2020). Also, we test the suitability of existing models (YASSO and RothC) for modelling soil C dynamics, which we apply to a hedgerow chronosequence from 13 years to more than 50 years post hedge establishment. Finally, we aim to develop a rapid assessment scorecard that also considers C management as part of results-based payment approaches.

The specific aims were as follows:

- Quantify the AGB and belowground biomass (BGB) of selected hedgerows using destructive sampling and analyse the C concentration of DM. Soil samples under the hedgerow and in adjacent land use were analysed for soil organic matter.
- Prior to destructive sampling, complete unmanned air vehicle (UAV) surveys to calculate corresponding AGB PV measurements of selected sites.
- Develop biomass to volume conversion factors using regression equations.
- Develop and test an inventory framework that can reflect the changes in hedgerow management using the UAV survey approach applied to a scaled-up survey. Estimate biomass CSC for different hedgerow types and management regimes in the pilot study area across two time steps using developed biomass–volume regression equations.
- Assess the suitability of the process-based models RothC and YASSO for SOC changes.
- Explore the impact on farm-scale emissions from the main farming systems that exist in Ireland.
- Develop a scorecard for assessment, along with best management practices for C and biodiversity.

2 Hedgerow Assessments and Biomass Modelling

2.1 Site Selection

The study design encompassed a wide range of hedgerow management and estimated age classes, following recommendations by Black *et al*. (2014a), to calibrate measured biomass and remotely surveyed volume measurements. A preliminary site characterisation was completed based on methods adapted from Crossland (2015). Expert visual assessment was completed to ensure suitability (Table 2.1 and Figure 2.1). Following an iterative shortlisting process and engagement with researchers, advisers and landowners, eight representative hedgerows were selected in two counties, four in County Carlow and four in County Wexford. All sites are located in the same agro-climatic region, as defined by Holden and Brereton (2004). The 10-year mean annual air temperatures were 10.06°C and 10.23°C and mean precipitation was 923 mm per year and 1136 mm per year for the Carlow and Wexford sites, respectively.

Based on the cross-sectional profile of the hedgerows, two main sub-classes were defined: (1) narrow regular-shaped hedges (type R, Table 2.1) with a box or straight side profile and/or with a width < 4 m, and (2) irregular wide hedges (type I, Table 2.1) that include tree lines that have a wider crown. Irregular hedgerows are less intensively managed, with occasional side flailing (e.g. > 3 years but no topping). Regular hedges are more intensively managed, with annual side flailing and topping. At each site, five representative points were randomly selected and georeferenced. A distance of 3 m on either side of the centre point was marked out, equating to a 6-m zone length for the five representative points at each site. The base and canopy width measurements were recorded following field determination of hedgerow width, following the guidance outlined by DEFRA (2007).

Table 2.1. Overview of selected sites according to age and management intensity

Site code	Type	Age (years est.)	Management intensity
JC1	I	40	Low
JC2	I	30	Low
PC	I	50+	Low[a]
DW	R	15	Low
KB1	R	50+	High
KB2	R	15	High
OP1	R	13	High
OP2	R	20	High

High management intensity refers to annual side flailing and topping. Low management intensity indicates occasional side flailing (every 3 years or more).

[a]Coppiced previously.

I, irregular wide hedges; R, narrow regular-shaped hedges.

2.2 Description of Field Sampling and Laboratory Analysis

Litter sampling (to estimate leaf biomass per m^2 of hedgerow sample plots) was completed from late August 2020 until leaf fall was complete. Litter traps were placed under hedgerows and litter was routinely collected during the litter fall period. For wider hedges (JC1, JC2, DW and PC; Table 2.2) a transect of litter traps was positioned to capture a scalable representation of litter fall during senescence. Litter was separated into stem and leaf, and fresh weights recorded. Samples were oven dried for 48 hours at 40°C. Dry weights were recorded to determine stem and leaf DM and the stem:leaf ratio. Finally, aggregate litter data were upscaled to a per unit area (m^2) and to zone areal extent to estimate litter fall for each zone.

Crown light transmission and density data were collected from each hedgerow sample zone prior to destructive sampling for biomass model development. Light transmission (τ) through the hedgerow crown was measured at four random ground points within the hedge sample zone using a ceptometer (Sunscan, DeltaT, Cambridge, UK). Lateral views of hedgerow sample zones were photographed prior to destructive sampling and image analysis was used to split the red, green and blue spectrum into three different channels, converting the red band to a black and white image, and to determine the lateral view open space (LVOS) ratio (Appendix 1, equation A1.1).

To calculate the total AGB and BGB (in line with IPCC reporting protocols), biomass was separated

Figure 2.1. One zone of five at each of the eight sites. Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

as follows: AGB was separated into living biomass with briar/understory material recorded separately. Deadwood was separated into attached and loose deadwood. All pools were fresh weighted prior to sub-sampling. Biomass was condensed using a wood chipper and weighted on a field scale that included conventional 220v weigh bars connected to an LCD display. Representative samples for each pool were oven dried at 70°C until constant weight to calculate dry mass. Oven dried biomass was further coarse ground (~10 mm) and fine milled to < 0.5 mm, subsampled in replicate and analysed for C using a LECO TruSpec CN analyser (Figure 2.2).

Tree measurements (diameter at breast height and height) were taken for up to five representative cut trees per sample zone. Two wood cookies, one from the main trunk and one from a secondary branch, were taken from each tree and dimensions were recorded (height, diameter) to calculate volume before drying to constant weight to calculate wood density.

To collect BGB, the topsoil adjacent to each sample zone was removed, to a depth of 1 m. All roots were cleaned in-field using a custom-built air-spade to clean at high air pressure ahead of weighing. Two sub-samples from each zone were collected for DM and C analysis. Sub-samples were further washed free of soil over a 2-mm sieve using a mains pressure washer to ensure no soil contamination of samples. BGB was also dried to constant weight at 70°C, milled and analysed for C as above. Hedgerow zone banks were restored where required and all hedgerow sample zones were replanted post biomass harvesting (Figure 2.3).

Soil samples were collected both directly under the hedgerow in so far as possible (within 0–30 cm) and from the adjacent land at a distance of 5 m, where possible. Soil samples were boxed and assigned to a soil laboratory set, dried to 40°C ± 3°C in a forced draught oven and sieved at 2 mm to remove stones and plant debris. Samples were analysed

Figure 2.2. Biomass pools and custom equipment.

Figure 2.3. Custom-built air-spade to clean root biomass in-field and samples being processed.

for C using a LECO TruSpec CN analyser. A 60-cm pit for bulk density sampling was dug and core ring samples of 50 mm diameter and depth were taken (non-intact samples). Bulk densities (g cm^{-3}) were calculated in accordance with ISO 11272:1998 – soil quality part 5.6 – determination of dry bulk density (Appendix 1, equation A1.2).

2.3 Description of the Unmanned Air Vehicle Survey

The hedgerow biomass plots were surveyed to estimate projected hedgerow volume in August 2020 using automated flights and photogrammetric procedures, as described by Green *et al*. (2019). Orthorectified digital surface models (DSMs; 3 cm resolution) for the 40 (eight sites, five replicates per site) ground referenced biomass plots were used to produce a digital elevation model (DEM) using ground points with no vegetation cover and Kriging to produce a surface elevation model (SEM). The hedgerow DEM was first used to determine the silhouette area (top view) of the hedgerow crown within each circular sample plot (0.05 ha). DEM raster cells within the plot and those with height values of > 0.5 m were selected and converted into a polygon layer using the raster calculator tool (ArcGIS Spatial Analyst). The hedgerow DEM was derived as the difference between the raster value DSM and the SEM heights. DEM models were converted to 3D triangulated irregular network (TIN) surface models in ArcGIS, using the 3D analyst extension (v10.8), to characterise hedgerow height, width, area and PV for each sample plot (Green *et al.*, 2019). The TIN surface models were also used to produce hedgerow cross-sectional profiles to further characterise and classify sampled hedges. The cross-sectional profiles were also used to check if ditches or banks were not included in the hedgerow PV estimates.

2.4 Biomass to Volume Conversion Factor Development Using Regression Equations

The derived PV of a defined hedge area is assumed to be related to hedgerow AGB. However, this relationship may vary because of hedgerow management. Intensively managed hedgerows may have smaller PVs but a much higher biomass per unit volume than less intensively managed or unmanaged hedgerows. To calculate the relationship between AGB and PV, see Appendix 1, equation A1.3. As the derived hedge PV is a “dead volume” estimate, open space beneath the crown is not considered. Green *et al.* (2019) provide a method for adjusting volume (AdjPV) for LVOS ratio (Appendix 1, equations A1.4 and A1.5). A further modification was included to allow the impact of differences in hedge density based on adsorption of light by the hedge crown to be included (Appendix 1, equation A1.6). BGB estimates were developed based on the second-order relationship with AGB (Appendix 1, equation A1.7). AGB and BGB were converted to C content using the mean C content of biomass sampled of $0.43\,\text{t C t}^{-1}$ biomass (dry weight (dwt)).

2.5 Hedgerow Biomass Carbon Results

The C concentration of biomass dry weight was consistent across all biomass pools at all sites, 43% (± 1%). Although no clear difference in AGB density was found between regular and irregular hedgerows, the hedge area per metre was generally higher in irregular hedgerows, meaning a much higher total biomass in irregular hedgerows (see table 2 from Black *et al.*, 2022). The mean root:shoot ratios (i.e. BGB:AGB) varied from 0.16 to 0.74 across hedgerow samples (Table 2.2). Sample hedges with codes PC and KB1, which were intensely managed, have higher root:shoot ratios. PC was an irregular ash-dominated hedge that has been coppiced in the past. KB1 is an old hedge that is flailed on the sides and top every year. In contrast, sample hedges JC1, JC2 and DW, which are infrequently flailed on the sides only, have lower root:shoot ratios.

2.6 Biomass Models and Equations for Volume to Biomass Conversion

Scatterplots and regression analysis of the AGB data and the TIN surface volumes generated two cluster

Table 2.2. Overview of key data from sample plots ($n = 40$). TIN model cross-sectional profiles were used to classify hedgerows as regular (R) or irregular (I)

Site code	Type	Age (years est.)	AGB (kg m^{-2})	BGB (kg m^{-2})	BGB/ABG ratio	PV ($\text{m}^3\,\text{m}^{-2}$)	Light transmission (τ) (no unit)	LVOS (no unit)	Hedge area ratio ($\text{m}^2\,\text{m}^{-1}$)
JC1	I	40	27.3 (6.0)	4.4 (1.9)	0.16 (0.08)	9.2 (0.9)	0.91 (0.03)	0.56 (0.05)	5.13 (0.45)
JC2	I	30	17.5 (5.1)	4.6 (2.3)	0.27 (0.11)	2.6 (0.9)	0.76 (011)	0.51 (0.0)	4.57 (0.31)
PC	I	50+	18.3 (9.9)	8.2 (6.2)	0.44 (0.18)	3.7 (2.9)	0.85 (0.03)	0.71 (0.06)	4.36 (0.72)
DW	R	15	24.7 (4.5)	5.4 (1.4)	0.22 (0.03)	2.4 (0.3)	0.88 (0.02)	0.47 (0.07)	2.73 (0.45)
KB1	R	50+	21.1 (4.5)	13.0 (3.5)	0.74 (0.48)	1.3 (0.4)	0.66 (0.03)	0.68 (0.06)	0.87 (0.07)
KB2	R	15	20.3 (6.1)	11.7 (5.0)	0.55 (0.19)	0.8 (2.7)	0.94 (0.07)	0.86 (0.14)	1.92 (0.13)
OP1	R	13	10.8 (3.9)	5.9 (6.1)	0.48 (0.33)	0.7 (0.3)	0.84 (0.01)	0.66 (0.11)	1.18 (0.03)
OP2	R	20	21.0 (3.9)	9.2 (1.8)	0.40 (0.18)	1.3 (0.3)	0.86 (0.01)	0.65 (0.03)	1.12 (0.03)

Values represent the mean and standard deviation (in parenthesis) for site-measured parameters.

Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

patterns for regular (R) and irregular (I) hedgerows (Figure 2.4, left panels). R hedgerows highlight a narrower hedgerow volume range, as these are typically more dense, with a smaller crown space, than I hedgerows. Based on the results, two biomass models were developed and model performance tested for these two major hedgerow types (see Appendix 1, equations A1.3 and A1.4). Model A used the unadjusted hedgerow volume model (see equation A1.3), suitable for situations without light transmission and LVOS data. The second model, model B, used equation A1.4 with adjusted volume (equation A1.6). The linear model coefficients, coefficients of determination (r^2) and residuals of observed and predicted values for the two hedgerow types are shown in Figure 2.4 and Table 2.3.

The solved coefficients were statistically significant with no significant bias in predicted AGB estimates (Table 2.3). Assessment of the model performance indicated satisfactory model calibration. Model B, which includes a volume adjustment based on LVOS and τ, improved model performance in relation to *F*-value, r^2 and root mean square error. Analysis of residuals showed no systematic bias in model predictions, with normally distributed residuals

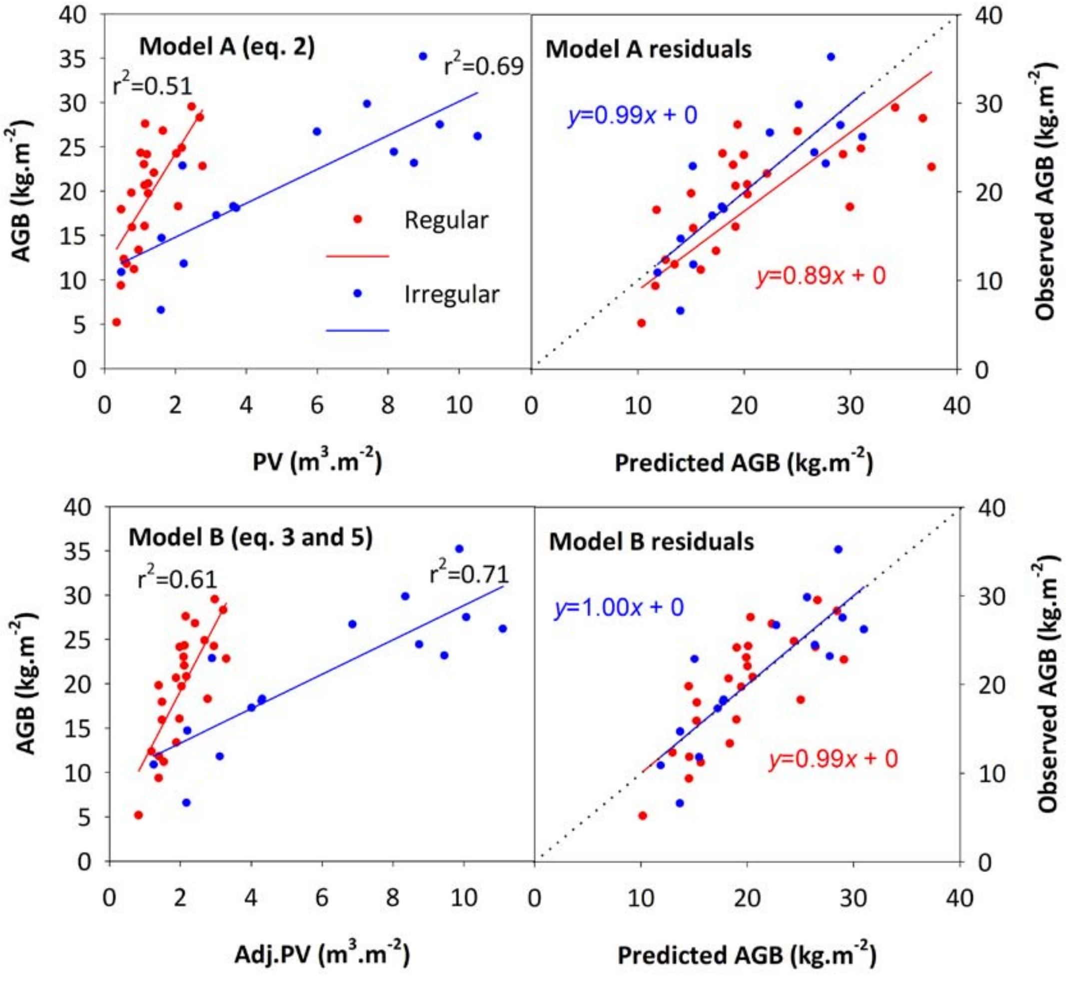


Figure 2.4. Regression analysis showing the fitted relationship between hedgerow AGB and hedge PV (a) and adjusted (Adj.) PV (c) for the two hedge types. Model residuals vs predicted hedge biomass values are shown for model A (b) and model B (d). The dotted black line in the right-hand panels represent the 1:1 slope and the solid lines are the fitted slope of observed and predicted values. The red and blue lines denote regular and irregular hedges, respectively. Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

Table 2.3. Model performance for models A and B and different hedgerow types, regular managed (R) and irregular (I)

Model	Hedge type	Equations	Coefficient	Value and standard error	*F*-value	RMSE (kg m^{-2})	Bias (kg m^{-2})
AGB		A1.3					
Model A	R		a	11.28 (1.93)***	23.75***	4.47	<0.001ns
			b	6.46 (1.32)***			
	I		a	10.95 (2.19)**	28.83***	4.38	<0.001ns
			b	1.91 (0.36)***			
AGB		A1.4 and A1.6					
Model B	R		a	12.17 (2.35)**	35.48***	4.02	<0.001ns
			b	7.65 (1.28)***			
	I		a	9.43 (2.34)***	31.34***	4.25	<0.001ns
			b	1.94 (0.34)***			
BGB	All	A1.7	a	–0.43 (0.51)ns	21.01***	3.73	1.69**
			b	0.85 (0.18)***			

All model coefficients and ANOVA *F*-value were significant at $p < 0.01$ or $p < 0.001$***. Bias estimates for all models were not significant (ns).**

ANOVA, analysis of variance; RMSE, root mean square error.

Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

at a *p*-value of 0.05 based on the Shapiro–Wilk test, confirming normality and indicating no heteroscedasticity issues.

Individual BGB to AGB regressions based on hedge profile types (i) based on equation A1.7 (Appendix 1) yielded non-significant coefficient values with high standard errors. A universal BGB-AGB model developed for all hedgerow types did not perform well either ($r^2 = 0.36$). Residuals analysis showed a systematic bias in the BGB model predictions with non-normal distribution of estimates. The application of the BGB model would result in a systematic underestimation of hedgerows with high BGB values.

3 Scaling Up: Estimating Carbon Stock Changes

3.1 Scaling to Estimates at County Level

A scaled-up hedgerow sampling approach, based on a two-point sampling system and using the National Forest Inventory (NFI) (Forest Service, 2017) 2 × 2 km point grid to identify all land cover types in Ireland, including hedgerows, was used. Hedgerow plot points were identified in the pilot study area covering counties Waterford and Wexford (Figure 3.1) and photogrammetry data from aerial imagery were used to assess changes in biomass stocks in sample plots over time. The radius of the circular sample plot was 12.62 m, the same used for the Irish NFI. Aircraft surveys of County Waterford were carried out by Bluesky Ltd in April 2015 and again in April 2020. County Wexford was surveyed in July 2016 and again in September 2019. Orthorectified DSMs (25 cm resolution) for 58 NFI plots were used to produce an SEM to characterise hedgerow height, width, area and PV for each NFI sample plot (Green *et al*., 2019). Cross-sectional profiles and PV were estimated for each hedgerow plot using the same approach used for UAV surveys. The sum of national- or county-level hedgerow area was derived from the systematic grid representative area and area of hedgerow within plot, calculated for different hedgerow profiles and management types, and C stocks calculated (see Appendix 1, equations A1.8–A1.10).

3.1.1 Time step analysis

Following data cleaning and classification error identification, 12 of the 58 hedgerow sample points from the NFI sampling framework were excluded. Errors were either definition based (i.e. were wooded/

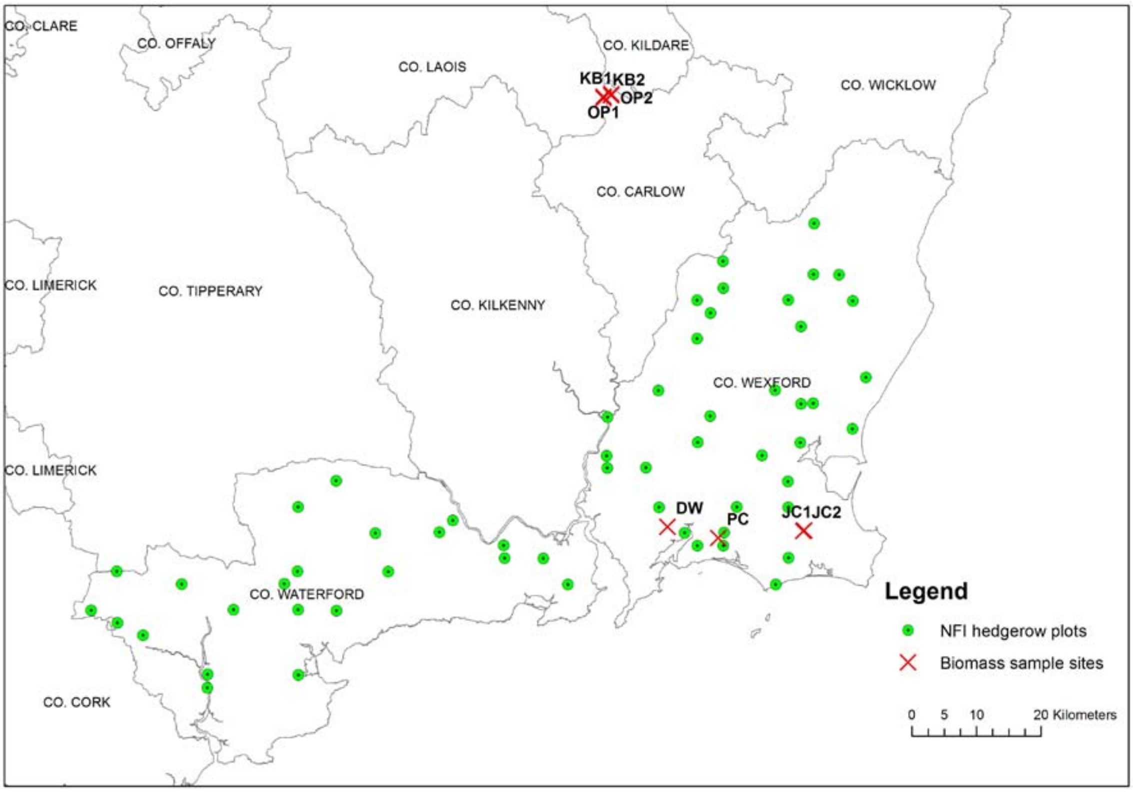


Figure 3.1. NFI grid points identified as hedgerows and biomass sample sites (red crosses). Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

forest areas, $n=6$) or processing issues, whereby shadows appeared as hedgerow crowns ($n=6$). From 2015 to 2019, four emergent hedgerows were identified (three grassland to hedgerow conversion and one in an urban area). Four plots were removed entirely between 2015 and 2019. Nineteen plots were cut back in the timeframe, of which nine were wide irregular hedgerows or tree lines prior to management. For example, plot 12 (Figure 3.2) had a width of 17 m with an irregular profile but was cut back to 6 m width by mid-summer 2019, resulting in significant losses of hedgerow volume and biomass. Twenty-four hedgerow plots were not managed or cut during the survey periods, resulting in hedge volume and biomass accumulation. A larger increase in crown cover, volume and biomass was found for irregular hedgerows than for regular hedges (Table 3.1).

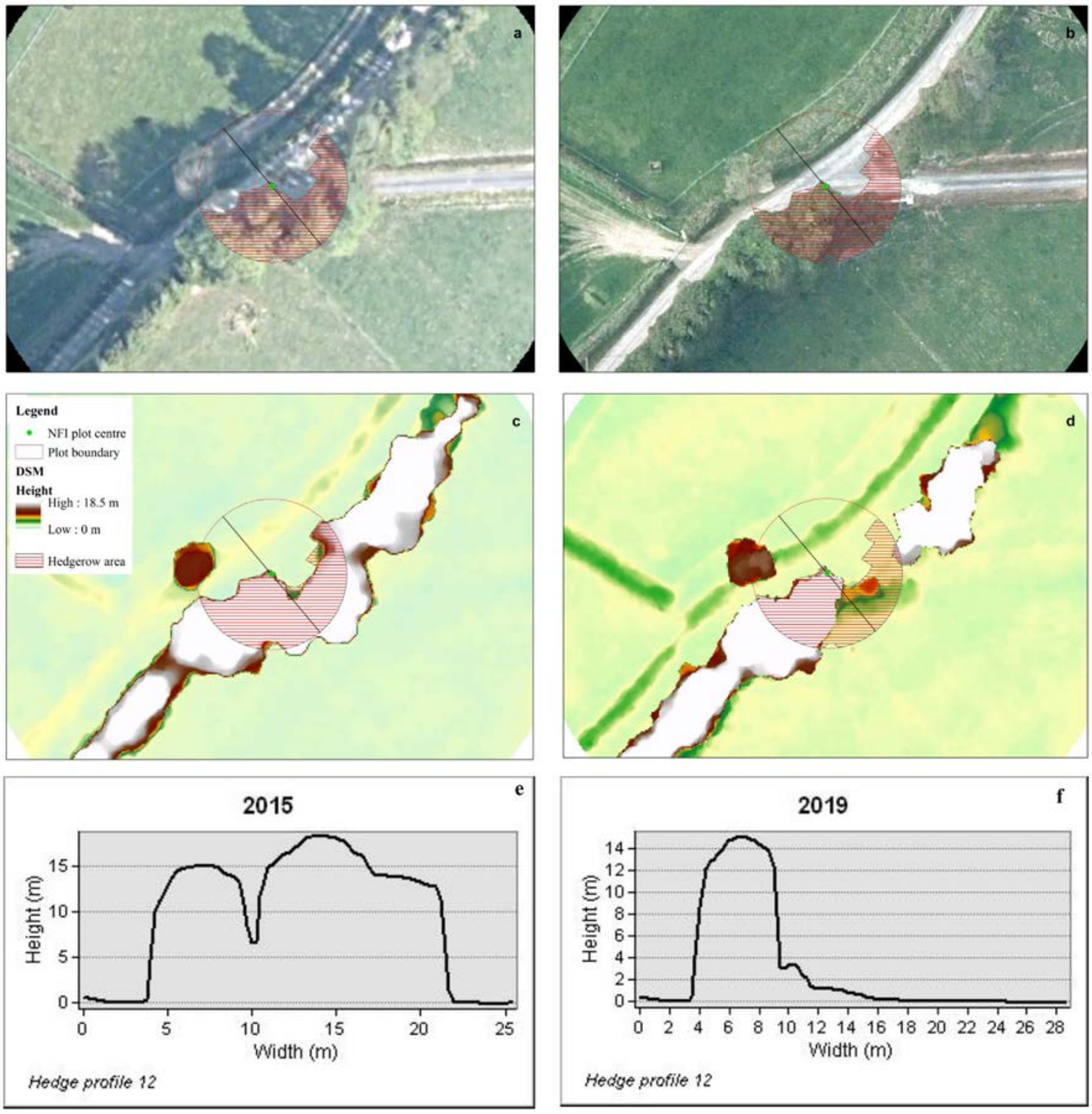


Figure 3.2. Aerial images (top panels) showing plot (plot 12) centre location, plot areas and hedgerow sample areas in 2015 (left) and 2019 (right). The middle panels show the DEM of the hedgerow area in 2015 and 2019. The dashed line through the centre of the plot is the cross-section transverse, used to compute the cross-sectional profiles shown in the bottom panels. Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

Table 3.1. Representative area and mean AGB, BGB C stocks and total biomass CSC for different hedgerow profile and management categories

Hedge class			Biomass C stocks (tC ha^{-1})		Representative area	
Profile	Management	Biomass CSC (tC ha^{-1} y^{-1})	AGB	BGB	2019 (ha)	% of area 2019
Regular	Cut back	–1.97 (1.68)^{b}	45.31 (31.72)^{a}	8.08 (5.23)^{a,b}	661	9.5
	Unmanaged	1.14 (1.00)^{a}	37.53 (28.18)^{a}	6.90 (5.12)^{b,c}	832	11.9
	Emergent	3.69 (0.12)^{a}	15.46 (nd)^{b}	3.02 (0.31)^{b}	226	3.2
	Removed	–3.58 (nd)	15.04 (nd)	5.72 (nd)^{c}	92	1.3
Irregular	Cut back	–2.69 (3.30)^{b}	67.74 (29.81)^{a}	12.47 (5.83)^{a}	2872	41.2
	Unmanaged	2.87 (2.72)^{a}	86.80 (36.2)^{a}	15.76 (7.04)^{a}	2387	34.2
	Emergent	–	–	–	–	–
	Removed	–8.34 (nd)	35.01 (nd)	6.71 (nd)	113	1.6

Stock and CSC values represent the mean and standard deviation (in parenthesis). nd indicates that there was only one or two sample plots. Mean biomass stock and stock change values with different superscript letters are significantly different based on analysis of variance Type III and Tukey’s honestly significant difference test where $p < 0.05$.

Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

3.2 Results of Scaled Estimates

There was a large variation in the range (–12.2 to 11.5 tC ha^{-1} y^{-1}) of estimated biomass CSC across different plots (Figure 3.3). The mean and median CSC was –0.29 and –0.03 tC ha^{-1} y^{-1}, respectively. Plot 13, an unmanaged irregular hedgerow, had the highest increase in C stocks (11.5 tC ha^{-1} y^{-1}). Plot 17 had the largest biomass C stock loss (61.5 tC ha^{-1}) over the period 2015 to 2019 due to the hedge being cut back from 17 m to 6 m.

No significant differences were detected in the overall mean biomass CSC of regular and irregular hedge profiles, but, within hedgerow profile groups, differences were found in mean values for management type. The highest mean biomass CSC was found for emergent hedgerows (3.69 tC ha^{-1} y^{-1}; Table 3.1) followed by unmanaged irregular profile hedgerows, which had a mean CSC of 2.87 tC ha^{-1} y^{-1} (Table 3.1). Unmanaged regular-shaped hedges (12% of hedgerows in study area) had a lower mean biomass sequestration rate of 1.14 tC ha^{-1} y^{-1} (Table 3.1). Management (trimming or cutback) of irregular hedgerows resulted in a mean biomass stock loss of –2.69 tC ha^{-1} y^{-1}. A smaller area (9.5% of the total hedge area) of regular hedges was cut back over the period and the mean biomass CSC loss was lower, when compared with managed irregular-shaped hedges (Table 3.1). The largest biomass losses occur

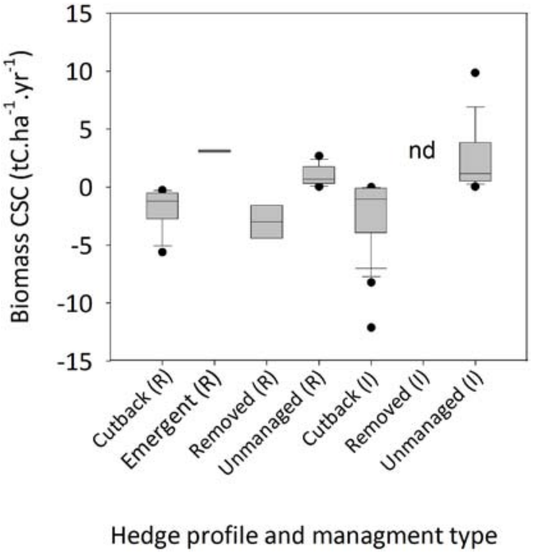


Figure 3.3. Box and whisker plot for biomass CSCs for different management (cut back, emergent, removed and unmanaged) and hedge profile (I, irregular; R, regular) types. The mean value is the line within the box and the standard deviation is the size of the box. The bars are the 5th and 95th percentiles and the black circles are outliers. The sample represents 46 NFI plots; nd indicates that one irregular profile plot was removed. Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

when irregular hedgerows are permanently removed (Table 3.1).

No significant interaction was found between profile and management type, but overall mean AGB and BGB across hedge profiles differed ($p < 0.001$) (Table 3.1). Irregular hedges had significantly higher overall mean AGB and BGB C stocks than regular hedgerow profiles.

Utilising the hedgerow data from the NFI grid sampling approach, between 2015 and 2019, a hedgerow area decrease of 8.1% was found (Table 3.2). Three plots were removed but four were planted (emergent) during that time period. A total of 407 ha of remaining hedgerow area was cut back or managed during the period. The mean AGB stock per hectare for remaining hedgerows was estimated to be 63–64 tC ha^{-1}, and a BGB of 11.2–11.9 tC ha^{-1} (Table 3.2). The mean total biomass stock of hedges before complete removal was 25.8 tC ha^{-1}. Emergent hedges had a lower mean C stock of 18.5 tC ha^{-1}. The total hedgerow for counties Wexford and Waterford is a net emission of –30.7 GgC, or 111 GgCO$_2$, for the period 2015–2019 (Table 3.2). This was associated with a larger C stock loss, due to cutback and removal of hedges, compared with C stock gains of new emergent hedgerows and unmanaged hedgerows.

3.3 Conclusions from Scaling Study

The county-level surveys suggest that biomass pools (between 2015 and 2019) represent a net emission due to the intensive management and permanent removal of hedgerows, which is greater than C accumulation in emergent and other hedgerows. The approach developed here has been tested for suitability for applying at a national scale. Duffy *et al*. (2022) indicated that there remain issues with respect to a time series in terms of extent and condition of non-forest woody biomass, along with methodological issues to map their change over time. This relies on repeated national datasets, which now exist, with three series of nationwide remote DEM data collected by Bluesky Ltd in 2015, 2019 and 2022. The approach piloted here proved to be sufficient for the inclusion of hedgerows in the national GHG inventory.

Table 3.2. Estimated changes in hedgerow area, AGB and BGB stocks, total biomass CSC and mean biomass CSC for the total, remaining, removed and emergent hedgerows over the period 2015–2019

	Total biomass CSC				Remaining (i.e. hedges present in 2015 and 2019)				Net change (2015–2019)			
			Net change (2015–2019)				Net change (2015–2019)		Removed		Emergent	
Parameter	2015	2019	Total	%	2015	2019[a]	Total	%	Total	%	Total	%
Area (ha)	7590	6977	–613	–8.1	7159	6752	–407	–5.7	205	2.7	226	3.0
AGB (GgC)	1189.1	1164.1	–25.0	–2.1	1163.1	1139.3	–23.7	–2.0	–26.0	–2.2	24.7	2.1
BGB (GgC)	218.5	212.8	–5.7	–2.6	213.6	208.0	–5.6	–2.6	–5.0	–2.3	4.8	2.2
Total C stock (GgC)	1407.6	1376.9	–30.7	–2.2	1376.6	1347.3	–29.3	–2.1	–31.0	–2.2	29.6	2.1
Mean AGB stock (tC ha^{-1})	58.3	55.9	–2.4	–4.1	64.6	63.3	–1.3	–2.0	–21.7		15.5	
Mean BGB stock (tC ha^{-1})	10.7	10.2	–0.5	–4.7	11.9	11.2	–0.7	–5.9	–4.1		3.0	
Mean biomass stock (tC ha^{-1})	70.0	66.1	–3.9	–5.6	76.5	74.5	–2.0	–2.6	–25.8		18.5	
Mean CSC (tC ha^{-1} y^{-1})			–0.3				–0.3		–5.9		3.7	

[a] Note that the remaining area in 2019 is due to both a decrease in the hedgerow area after being cut back and an increase in area due to existing hedgerow expansion.

Reprinted from *Science of the Total Environment*, Vol 871, Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and Sullivan, L. Biomass carbon stocks and stock changes in managed hedgerows, copyright (2023), with permission from Elsevier.

4 Modelling Soil Organic Carbon

4.1 Comparison of Process-based Models for Soil Organic Carbon

SOC stocks were calculated and analysed (Appendix 1, equation A1.11). Directly measured AGB, BGB, litter inputs and management data were used as model inputs. Additional management data were derived based on survey data over a 5-year period, owing to a lack of management data (survey information, section 2.3). This approach assumes that AGB stock change losses are due to management. Annual C inputs (annual biomass, litter and management) for different DOM, required to run the YASSO and RothC models, were reconstructed over a 50-year time series. Annual AGB and BGB stocks (i.e. standing stocks (kg m^{-2})) were modelled using the Chapman–Richards function based on the hedgerow biomass data (Appendix 1, equations A1.12–A1.17).

Finally, the amount of C accumulated in hedgerows is a function of the C density (e.g. AGB, BGB, DOM, etc.) and the change in hedgerow width. Importantly, irregular and regular hedgerows have similar AGB densities but vary considerably in width. Irregular hedgerows in the study area showed width increases from 0.5 m at establishment to over 5 m after 50 years (Black *et al.*, 2022). Irregular hedgerows are generally maintained at 4 m width as required under agricultural payment schemes and currently prescribed best practice. Regular hedgerow width in this study varied from 0.8 to 1.9 m but was relatively consistent: 1.2 m over the entire age series for regular-shaped hedgerows. Changes in hedgerow width per metre of hedgerow length in irregular hedges was modelled using the same equation used to derive annual BGB and AGB (equation A1.12). The solved coefficients are shown in Appendix 1. For a more detailed explanation of the set-up of the YASSO and RothC models, see Appendix 2.

4.2 Process-based Model Results

4.2.1 YASSO carbon fluxes

Fine root and litter C inputs into the DOM pools varied from 0 to 0.02 kgC m^{-2} y^{-1} for both regular and irregular hedges (Figure 4.1). Fine root turnover shows an

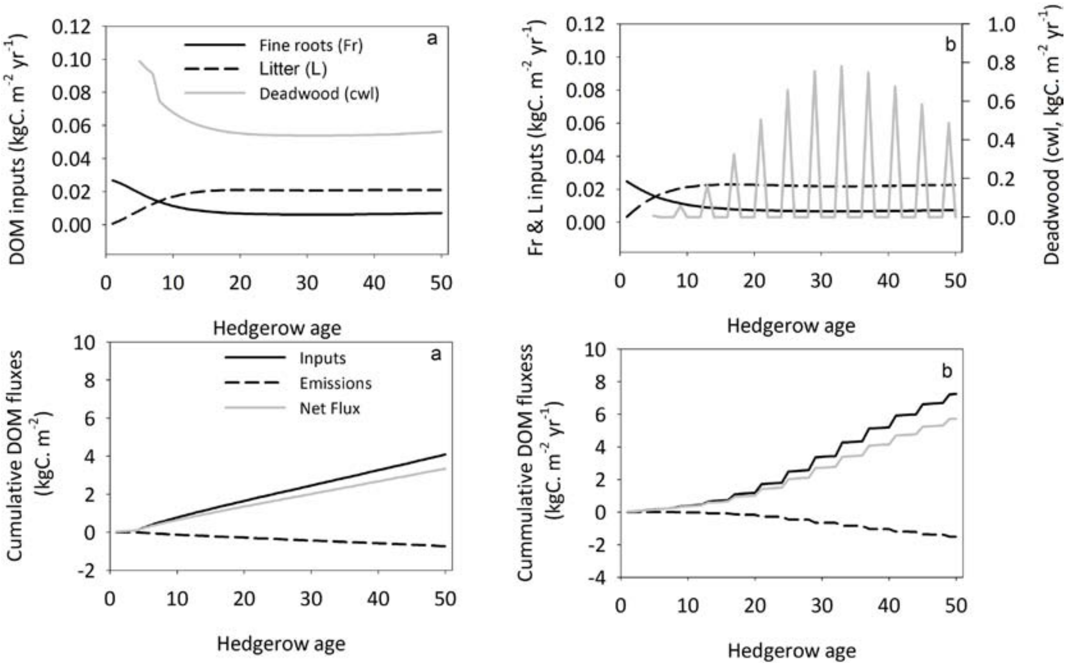


Figure 4.1. DOM inputs (top panels) and cumulative DOM C fluxes (bottom panels) for regular (a) and irregular (b) hedges over a 50-year period. Note the different right axis for deadwood inputs for irregular hedges (top panel b).

exponential decline, compared with an exponential increase in litter inputs (Figure 4.1). Deadwood (*cwl*) inputs in regular hedges, which are cut every year, declined from an initial input of 0.1 kgC m^{-2} y^{-1} to a steady level of 0.06 kgC m^{-2} y^{-1} by year 20 (Figure 4.1). In contrast, *cwl* inputs in irregular hedges, which are harvested every 5 years, are considerably larger, starting at 0.002 kgC m^{-2} y^{-1}, peaking at 0.77 kgC m^{-2} y^{-1} at 30 years and followed by a decline to 0.48 kgC m^{-2} y^{-1} by year 50 (Figure 4.1). Therefore, the cumulative inputs into the DOM pool are higher for irregular than for regular hedges. Cumulative emissions of C back to the atmosphere from irregular hedges over the 50-year period (–1.51 kgC m^{-2}) were higher than those from regular hedges (0.74 kgC m^{-2}). The modelled total net accumulation of C in the DOM pool after 50 years was 3.34 and 5.72 kgC m^{-2} for regular and irregular hedges, respectively (Figure 4.1).

4.2.2 Soil and dissolved organic matter carbon stock changes

In general, SOC stocks and stock changes (ΔSOC) increased for both regular and irregular hedge chronosequences using both YASSO and RothC as hedgerows age (Table 4.1 and Figure 4.1). Changes in SOC were driven by accumulation of C in the humic pools, with the percentage of humic C increasing from

Table 4.1. Chronosequence site information, SOC stocks for paired plots with different land uses and inferred SOC stock changes (ΔC)

Site code	Land use	Soil type	Age (years)	SOC (kgC m^{-2})	ΔSOC (kgC m^{-2})	YASSO SOC ΔSOC (kgC m^{-2})	RothC SOC ΔSOC (kgC m^{-2})	RothC SOC[b] ΔSOC (kgC m^{-2})
JC1	Hedge (I)	Gley soil	40	15.20 (2.31)				
	Cropland	Gley soil		8.19 (1.69)	7.01	4.15	3.16	6.16
JC2	Hedge (I)	Brown earth	30	11.13 (2.34)				
	Grassland	Brown earth		8.11 (1.35)	3.02	2.72	2.35	
PC	Hedge (I)	Brown earth	50	10.17 (0.90)				
	Grassland	Brown earth		9.45 (1.48)	0.72	5.72	0.90	
DW[a]	Hedge (I)	Brown earth	15	12.24 (0.94)				
	Cropland	Brown earth		6.65 (0.65)	5.59	0.68	1.73	4.07
	Grassland	Brown earth		7.49 (1.90)	4.75	0.68	1.51	3.82
KB1	Hedge (R)	Luvisol	50	10.56 (3.27)				
	Cropland	Luvisol		6.40 (1.49)	4.16	3.33	2.32	
KB2	Hedge (R)	Luvisol	15	10.08 (2.31)				
	Cropland	Luvisol		8.74 (1.59)	1.34	0.92	0.69	
OP1	Hedge (R)	Brown earth	13	10.07 (0.50)				
	Grassland	Brown earth		7.81 (1.18)	2.26	0.85	1.36	
OP2	Hedge (R)	Brown earth	20	8.31 (1.61)				
	Grassland	Brown earth		6.68 (1.6.8)	1.63	1.33	1.45	

SOC values represent a mean for each soil and land use type (*n* = 10 per site/land use) with the standard deviation in parenthesis. ΔSOC is the difference of the mean hedgerow and paired land use type. The YASSO ΔSOC represents the modelled accumulation of SOC for each site and soil type.

[a] The paired plot for the site DW included a cropland on one side and a grassland on the other side of the hedgerow.

[b] RothC initialised assuming grassland and/or previous hedge as land use.

I, irregular hedges; R, regular hedges.

84% ± 4.2% to 95% ± 2.3% on inclusion of hedgerows. However, annualised ΔSOC values show a declining trend as the hedgerow age increased (Figure 4.1). The mean annual ΔSOC for croplands converted to hedgerow was 0.18 ± 0.14 kg m^{-2} y^{-1}, compared with 0.13 ± 0.12 kg m^{-2} y^{-1} for grassland conversions to hedgerow. Mean annual ΔSOC values for irregular hedges (0.20 ± 0.15 kg m^{-2} y^{-1}) were slightly higher than those for regular hedgerows (0.11 ± 0.05 kg m^{-2} y^{-1}). The small sample numbers limit statistical testing of implied mean values, so it is not possible to discuss the significance of ΔSOC values across hedge type or land use transitions. Irregular hedges did, however, exhibit a larger variation in implied ΔSOC values when compared with regular hedgerows.

The inferred ΔSOC estimates for hedgerows based on our chronosequence approach is 0.01–0.39 kgC m^{-2} y^{-1}, equivalent to 0.1–3.9 tC ha^{-1} y^{-1} (to a depth of 30 cm). This is comparable with another paired plot approach published by Biffi *et al*. (2022), who report ΔSOC values of 0.84–2.28 tC ha^{-1} y^{-1} over a grassland converted to hedgerow chronosequence. Based on IPCC's (2019) 20- or 50-year steady state assumption, our reported annualised ΔSOC values are 2.27 tC ha^{-1} y^{-1} or 0.48 tC ha^{-1} y^{-1}, respectively. This is slightly higher than the reported range of 0.9 tC ha^{-1} y^{-1} or 0.3 tC ha^{-1} y^{-1} for a steady state at 20 or 50 years, based on a meta-analysis by Drexler *et al*. (2021). SOC accumulation appears to decline as hedgerows age (Figure 4.2), which is consistent with other findings (Drexler *et al*., 2021; Biffi *et al*., 2022). Initial model runs did not yield a good agreement between the measured and modelled ΔSOC values with YASSO or RothC when hedgerows were young (Figure 4.2).

Unlike YASSO, RothC can consider the impact of previous land use. Drawing on anecdotal evidence of previous land use, an optimised RothC run resulted in better agreement with measured SOC. Both models predict that more DOM is accumulated in irregular hedges (0.11 kgC m^{-2} y^{-1}) by year 50, when compared with regular hedges (0.06 kgC m^{-2} y^{-1}). RothC modelling indicated a period > 50 years for SOC to reach steady state, and so the steady state assumption may not accurately reflect soil C dynamics due to land use transition from another land use to hedgerow (Black *et al*., 2014b). Also, the chronosequence and paired plot assumption that management is the same across a previous land use and in years following hedgerow establishment may not be valid.

4.2.3 Ecosystem stock and fluxes

Figure 4.3 shows theoretical trends in C stock and fluxes for managed regular and irregular hedges. A comparison of modelled C stock densities over time shows that regular hedges have a higher peak AGB and BGB C stock density than irregular hedges (Figure 4.3, top panels). Irregular hedges accumulate more DOM because of a higher input from cutting (Figures 4.1 and 4.3). The models suggest that regular hedge total C density initially accumulates faster than that of irregular hedges and reaches an asymptote point at *c*.30 years. In contrast, irregular hedge biomass density has a slower initial C density, but the total C stock reaches a steady state by 50 years.

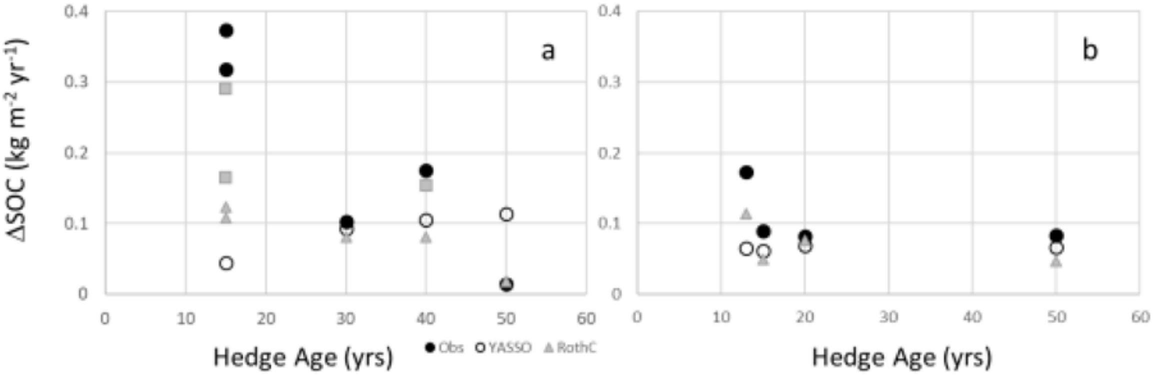


Figure 4.2. Measured annualised (observed ΔSOC, open circles) and modelled ΔSOC using YASSO (black circles) and RothC (grey triangles) stock changes across the irregular (a) and regular hedge (b) chronosequences. Grey squares indicate separate model runs where land use was altered to better match modelled and measured ΔSOC.

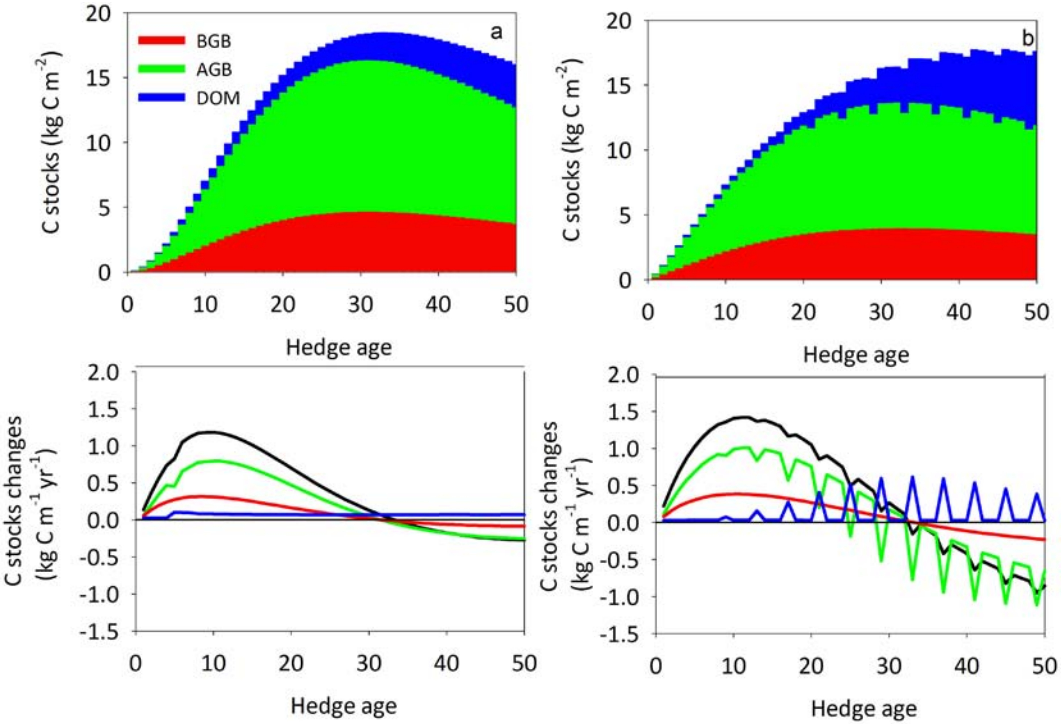


Figure 4.3. Modelled AGB, BGB and DOM stocks (top panels), and stock changes and NEE (bottom panels) of regular (left panels) and irregular hedgerows (right panels) over a 50-year time period.

The average sequestration of C in the AGB, BGB and DOM of regular hedges by year 30 is 0.39, 0.15 and 0.07 kgC m^{-2} y^{-1}, respectively. For the 50-year period, this declines to 0.18, 0.07 and 0.07 kgC m^{-2} y^{-1}. For irregular hedges, the AGB, BGB and DOM pool accumulate 0.32, 0.13 and 0.09 kgC m^{-2} y^{-1} by year 30. This decreases to 0.18, 0.07 and 0.11 kgC m^{-2} y^{-1} by year 50. The total removal rate, expressed as a density per m^2 by year 50, is higher for regular hedges (0.61 kgC m^{-2} y^{-1}) than for irregular hedges (0.54 kgC m^{-2} y^{-1}).

When C stock changes are expressed per linear hedge metre (Figure 4.3, bottom panels), irregular hedges sequester more C in all pools than regular hedges, particularly in the first 30 years. Both hedge type NEE removals increase to a peak of 1–1.5 kgC m^{-1} y^{-1} by year 10, followed by a decline and transition to a net emission after years 33–35 (Figure 4.3). Irregular hedges have a net removal of 28 kgC m^{-1} y^{-1} over the first 33 years post establishment, compared with 21 kgC m^{-1} y^{-1} for regular hedges. The mean NEE removal for the 30-year period is 0.84 and 0.63 kg m^{-1} y^{-1} for irregular and regular hedges, respectively. Biomass C pools and NEE are net emissions after year 33, but C continues to be sequestered in the DOM pool.

Options for SOC stock changes of hedgerows in GHG inventory reporting include (1) a tier 1 or 2 approach based on measured SOC changes across different land uses (Black *et al*., 2014b; Drexler *et al*., 2021; Biffi *et al*., 2022) or (2) developing models to estimate SOC changes based on management activity data. Cardinael *et al*. (2018) provide the IPCC tier 1 SOC values based on 12 measured shelterbelt sites. Tier 2 approaches that reflect national circumstances would require a more intensive sampling programme than were achievable within the time and budget constraints of this project to ensure that a *Δ*SOC based on the chronosequence approach meets rigorous statistical analysis. Application of tier 3 models for hedgerows offers a plausible alternative. However, to achieve consistent model outputs that align with measurements, long-term previous land use information is required (Figure 4.2).

4.3 Conclusions from Process-based Modelling of Soil Organic Carbon

Consistent with biomass surveys conducted in counties Wexford and Waterford, which suggest that established managed hedgerow biomass account for net emissions (Black *et al*., 2022), our theoretical NEE model suggests that the NEE of intensively managed hedgerows is a temporary removal for at least the first 30 years after establishment. This analysis confirms that wider, more irregular hedgerows have a higher sequestration potential (Falloon *et al.,* 2004; Axe *et al*., 2017; Black *et al*., 2022). Therefore, management that fosters irregular wider hedgerows along with new hedgerows has greater potential to sequester C in the landscape. In addition, management strategies to sustain C stocks in older managed hedgerows need to be developed. A major implication of our finding is that the potential ability of hedgerows to sequester C over the long term (Black *et al*., 2014a; Drexler *et al*., 2021; Biffi *et al.*, 2022) may be overestimated, particularly in intensively managed hedgerows. Scaling up local chronosequence study results to the landscape or national level (e.g. Black *et al*., 2014a; Biffi *et al.*, 2022) may be based on oversimplified assumptions that do not consider the dynamics of C fluxes over time and under different management systems. Therefore, more efforts are required to develop mechanistic models specifically on C dynamics in hedgerow systems. Although forest C models may provide some insight into how these models need to be formulated, there appear to be other hedgerow-specific factors that need to be taken into account.

5 Impact of Hedgerows on Farm-scale Emissions

As outlined in section 1.1, the European Green Deal set the objective of climate neutrality for the EU by 2050 (EC, 2019). This ambition, along with meeting national climate sectoral ceiling targets, will rely on land use and management that both enhances existing carbon sinks and reverses the decline in decreasing carbon sinks. In addition, the LULUCF sector will now have a target of enhancing carbon sinks to 310 $MtCO_2e$ (CO_2 equivalent) by 2030 under the revised LULUCF regulations, which are expected to come into force in 2024. This target, similar to other EU targets, will be divided among Member States via an effort-sharing process. Under this process, Ireland must reduce LULUCF emissions by 13.6% relative to a baseline that is set between the years 2016 and 2018. Agriculture is the major land use in Ireland, with 64% of the area in the Agricultural Census of 2020 reported as "agricultural area used" (CSO, 2021). Therefore, the realisation of climate ambitions in Ireland is highly dependent on land use and management decisions made on farm. In parallel, the concept of carbon farming has generated interest at farm scale, and is considered to have a role in achieving EU climate targets (COWI *et al.*, 2021). Although it was beyond the scope of this research to explore the farm-scale climate regulation potential of hedgerows on individual farms, the project still aimed to assess the impact of hedgerows on the main farming systems using generalised data, with a view to garnering insights into the importance of hedgerows on farms and understanding the opportunities offered by them.

5.1 Farm-level Assessment

To assess the impact of hedgerows on farming systems, the modelled hedgerow inputs and outputs were applied to the "average" dairy, beef and arable farming systems in Ireland. Data from the National Farm Survey Sustainability Report (Buckley and Donnellan, 2021) were applied to characterise the main farming systems (dairy, beef and arable) in Ireland, including averages of GHG emissions, farm activity and hedgerow area (Table 5.1 and Figure 5.1). Outputs from Chapter 4 were applied to assess the potential emissions and removals associated with hedgerows (Table 5.2).

Table 5.1. Activity data for the average dairy, beef and arable farm

Farm enterprise	Dairy	Beef	Arable
Dairy cows	83		
Suckler cows		28	
Heifers	10	2	
Calves	47	25	
1–2 years, male	8	4	
1–2 years, female	15	7	
2 years	2	2	
Bulls	1	1	
UAA (ha)	61	32	61
Fertiliser (kg nitrogen)	150	60	150
Hedge (% UAA)	2.73	2.93	2.67

UAA, utilised agricultural area.

5.2 Opportunity of Hedgerows for Reducing Farm-scale Emissions

Using the activity data in Table 5.1, the CO_2e emissions per hectare and per farm were calculated. The GHG emission balances per hectare were 9.3, 5.0 and 1.4 $tCO_2e\,ha^{-1}\,y^{-1}$ for the average dairy, beef and arable farm, respectively (Figure 5.1a). On a whole farm basis, emissions varied from 84 $tCO_2e\,farm^{-1}\,y^{-1}$ for arable to 568 $tCO_2e\,farm^{-1}\,y^{-1}$ for dairy (Figure 5.1b). Methane accounted for the bulk of livestock emissions (76% for dairy and 70% for beef farms), while nitrous oxide accounted for 82% of arable emissions. Assuming that 2.73%, 2.93% and 2.67% of dairy, beef and arable farm areas, respectively, are composed of hedgerows, using the data for the quantity of CO_2 sequestered by regular hedgerows would give farm systems equivalents associated with hedgerow management of ~7%, 13% and 43% of dairy, beef and arable farm emissions (Table 5.3). Switching management regime to either 50% or 100% of unmanaged hedgerows could increase C sequestration considerably, offsetting between 13%

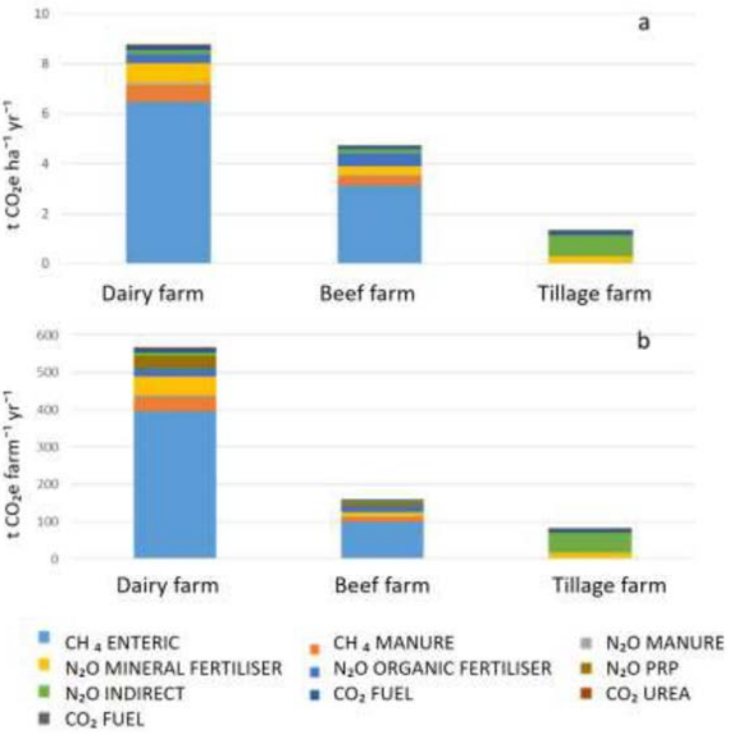


Figure 5.1. GHG emissions expressed on a per hectare and per farm basis. CH_4, methane; N_2O, nitrous oxide; PRP, pasture, range and paddocks.

Table 5.2. CO_2 potential equivalent C and CO_2e expressed per hectare per year for biomass, SOC and combined CO_2 for biomass SOC

	Biomass[a]		SOC[b]		
Hedgerow type	tC ha y^{-1}	tCO_2e ha y^{-1}	tC ha y^{-1}	tCO_2e ha y^{-1}	Total (tCO_2e ha y^{-1})
Managed	6.1	22.37	1.08	3.96	26.33
Unmanaged	5.4	19.80	3.19	11.70	31.50
	Mean hedge width	Hedge length (km^{-1})	Sequestration per unit length (tCO_2 km^{-1})	Increase per km – scaling factor	
Managed	1.2	8.3	3.17		
Unmanaged	4	2.5	12.60	3.97	

The scaling factor represents the value to convert managed to unmanaged per km.

[a] Biomass values derived from mean NEE removals for the 30-year period are 0.84 and 0.63 kg m^{-1} y^{-1} for irregular unmanaged and regular managed hedgerows (section 4.2.3).

[b] SOC values derived from mean values for managed and unmanaged hedgerows (section 4.2.2, Table 4.1).

and 26% of dairy farm emissions, 26% and 52% of suckler farm emissions and 86% and 172% of tillage farm emissions. Key factors will mitigate this large sequestration rate: (1) not all hedgerows on farms are intensively managed and a review of the EU Land Use and Land Cover Survey transects in 2012 and 2015 as part of the BRIAR project indicates a 2:1 occurrence of unmanaged to managed hedgerows; (2) many farmers are unlikely to switch to 100% more unmanaged hedgerows; and (3) roadside safety means that a proportion of hedgerows will continue to require routine management.

5.3 Conclusions

Hedgerows are an important element in agricultural landscapes. While scope to harness the potential of hedgerows for climate change mitigation and other

Table 5.3. Farm system emissions equivalent associated with hedgerow management

	Dairy	Beef	Arable
Farm emissions (tCO_2/farm)	568.39	160.36	83.91
Emissions assuming all hedges managed (tCO_2/farm)	37.2	21.0	36.4
% offset	7%	13%	43%
Emissions assuming hedges managed irregularly (tCO_2/farm)	147.87	83.25	144.62
% offset: 50% of hedges	13%	26%	86%
% offset: 100% of hedges	26%	52%	172%

ecosystem services exists, it is important to note that this research finds that intensive management practices in particular represent a key bottleneck in utilising hedgerows for the delivery of climate ambitions. The retention of existing hedgerows on farms is important. Assuming full coverage of regular managed hedgerows, the CO_2 sequestered by regular hedgerows could be equivalent to ~7% on the average dairy farm compared with 43% on the average arable farm. This is a reflection of the high level of emissions associated with the average dairy farm and heightens the importance of hedgerow retention, reduced hedgerow management intensity and increasing the area of new hedgerows at farm scale. Apart from additional new hedgerows, adapting to a less intensive management regime where possible creates an important opportunity to increase the equivalent benefit of hedgerows.

6 Integrated Scorecard Development

Results-based payment approaches are becoming an integral part of agri-environment schemes. A key element of results-based approaches is the development of rapid assessment scorecards to assess the (ecological) quality of habitats. Scorecards are designed based on specific ecological principles reflecting factors relating to ecological integrity and damaging activity. Rapid assessment scorecards allow for the quick assessment of habitat quality, based on a number of easily assessed indicators. The demand for scorecards covering a range of different habitats is increasing, and several scorecards have been developed to assess the ecological quality of hedgerows (as part of European Innovative Partnerships (EIPs), EU LIFE and Department of Agriculture, Food and the Marine (DAFM) pilot and research projects).

This task aimed to develop and design a practical, easy to use integrated scorecard (for biodiversity and carbon) for hedgerows. The task aimed to revise existing scorecards but with a carbon focus. A number of parameters will be universal to ecological and carbon storage quality (e.g. hedge height and density); however, a number of the parameters for ecological quality will be of less relevance for carbon storage quality.

6.1 Approach

A total of six existing hedgerow scorecards relevant to Irish conditions were identified by the Farm-Carbon team (see Table 6.1). These included scorecards designed for EIPs (Biodiversity Regeneration in a Dairying Environment (BRIDE); Hen Harrier; Farm Payments for Ecology and Agricultural Transitions (Farm PEAT)), for agri-environment schemes (Results Based Environment Agri Pilot Programme (REAP); for DAFM projects and for research (FarmECOS).

A hedgerow assessment was completed at each of the eight study hedgerow sites (see section 2.5, Table 2.2) utilising the six hedgerow scorecards (i.e. those designed for biodiversity assessment). Results were assessed to determine what lessons could be learned to improve the design of existing scorecards (and inform the design of a universal scorecard suitable for future EIPs, EU LIFE projects, agri-environment schemes, etc.). Scorecards were also assessed to determine what C-related parameters (as indicated in literature and based on the outcomes from field-level assessment of carbon stocks), and weighting of parameters, could be included in a biodiversity-/carbon-integrated scorecard.

Following the review and implementation of scorecards, an anonymous survey of farmers ($n=30$) was undertaken to gain further insight into farmers' hedgerow management approaches and how practical some management strategies could be, while considering policy requirements. Outcomes from this survey helped inform the design of an integrated scorecard and gave insight into what variables farmers

Table 6.1. Projects with scorecards relating to hedgerow quality, and hedgerow structural variables likely to influence C storage and sequestration

Project name	Further details	Width	Height	Gaps	Management
REAP	https://www.gov.ie/en/service/64388-results-based-environment-agri-pilot-programme-reap/	No	Yes	No	No
BRIDE	https://www.thebrideproject.ie/	No	Yes[a]	Yes	Yes
DAFM	Pers. comm.	Yes	Yes	Yes	Yes
FarmECOS	https://www.teagasc.ie/environment/biodiversity--countryside/research/current-projects/farm-ecos/	Yes	Yes	No	Yes
Hen Harrier	http://www.henharrierproject.ie/	Yes	Yes	Yes	No
Farm PEAT	https://www.farmpeat.ie/	Yes	Yes	Yes	No

[a]Includes a variable on topping history.

believed should and should not be included in such a scorecard.

6.2 Existing Scorecard Review

Following the collation, review and implementation of existing scorecards, the following observations were apparent.

6.2.1 A number of metrics were universal to all scorecards, but grading differed

Some metrics were universal to all scorecards (e.g. height variables; Table 6.1). This reflects broad agreement among the various EIPs, EU LIFE and DAFM projects on what variables could be measured to reflect the ecological value of a hedgerow. However, while the metric measured may be universal between scorecards, what was considered the “best” height for hedgerows differed significantly between scorecards. For example, the REAP scorecard considered hedgerows > 1.5 m in height to be optimal, whereas the FarmECOS scorecard considered hedgerows > 4.0 m in height to be optimal.

6.2.2 There was significant variability in hedgerow ecological score, depending on scorecard used

A key limitation with existing scorecards was the variability in hedgerow scores, depending on the scorecard used (i.e. lack of consistency between scorecards) (Table 6.2). On occasion, there was broad agreement on score achieved, e.g. hedge JC2 scored > 80% across all scorecards and hedge KB1 scored < 40% across all scorecards (Table 6.1). However, for some hedgerows, the range in scores was significant, e.g. from 33% to 100% for hedgerow KB2. While some variability in scores is expected, significant variation between scorecards can indicate flaws in the design of a scorecard, particular in relation to what variables are being valued and how they are being valued (see section 6.2.1).

6.2.3 All scorecards included metrics that could be used to assess multiple ecosystem services (including carbon), but weighting did not reflect their value to multiple ecosystem services

It was apparent that most scorecards already included several metrics that are relevant for the assessment of C storage and other ecosystem services, even if C storage was not the primary focus (e.g. structural variables, see Table 5.3). However, as the focus of existing scorecards was on assessing ecological quality, typically the weighting associated with various metrics did not reflect their value to multiple ecosystem services. For example, in the Common Agricultural Policy scorecard, hedgerow height and width variables (key metrics for biodiversity and C storage) were valued more or less the same as species richness variables (metrics of lower consideration for C storage). The majority of scorecards focused on only one ecosystem service (e.g. biodiversity, as was their remit) as opposed to scoring for multiple ecosystem services.

Table 6.2. Hedgerows assessed based on six existing scoring systems: site codes, type and age, based on Table 2.1 site characterisation data

Site code	Type	Age (years est.)	REAP	BRIDE	DAFM	FarmECOS	Hen Harrier	Farm PEAT	Hen Harrier[a]	Farm PEAT[a]
JC1	I	40	67%	98%	60%	60%	50%	50%	Moderate	Moderate
JC2	I	30	100%	100%	95%	81%	83%	83%	Good	Good
PC	I	>50	67%	70%	70%	57%	83%	83%	Good	Good
DW	R	15	100%	100%	80%	74%	83%	50%	Good	Moderate
KB1	R	>50	0%	38%	5%	36%	17%	33%	Poor	Poor
KB2	R	15	100%	40%	50%	57%	50%	33%	Moderate	Poor
OP1	R	13	100%	50%	60%	57%	50%	50%	Moderate	Moderate
OP2	R	20	100%	50%	40%	50%	50%	50%	Moderate	Moderate

[a]**Hen Harrier and Farm PEAT assessments were categorised on ordinal variables, and these were converted to numeric, based on mid-point.**

6.3 Development of an Integrated Scorecard

Following a review of existing scorecards (section 6.2), coupled with the results from the measured site indicators (Table 5.3), and incorporating lessons learned from Chapter 2 of this study, an integrated scorecard is proposed (see Figure 6.1). The metrics included were selected and weighted to reflect the most relevant variables (from existing scorecards) in relation to biodiversity and new C metrics (as derived from the Farm-Carbon study and expert opinion).

The integrated scoring system consisted of the following points.

6.3.1 Ecological and C integrity

- Key variables here included the density of hedgerows, their height and width, and the frequency of gaps. These variables are important for both biodiversity and C storage, and thus the weighting of scores reflects that (i.e. 60% of the overall maximum score was allocated to these variables).
- Variables relating to positive indicator species and frequency of negative indicators were also included in this category. These variables are more associated with ecological quality, and thus the weighting of score was reduced (in this instance to 15% of the overall score).

6.3.2 Age and management concerning the frequency of side-trimming and topping

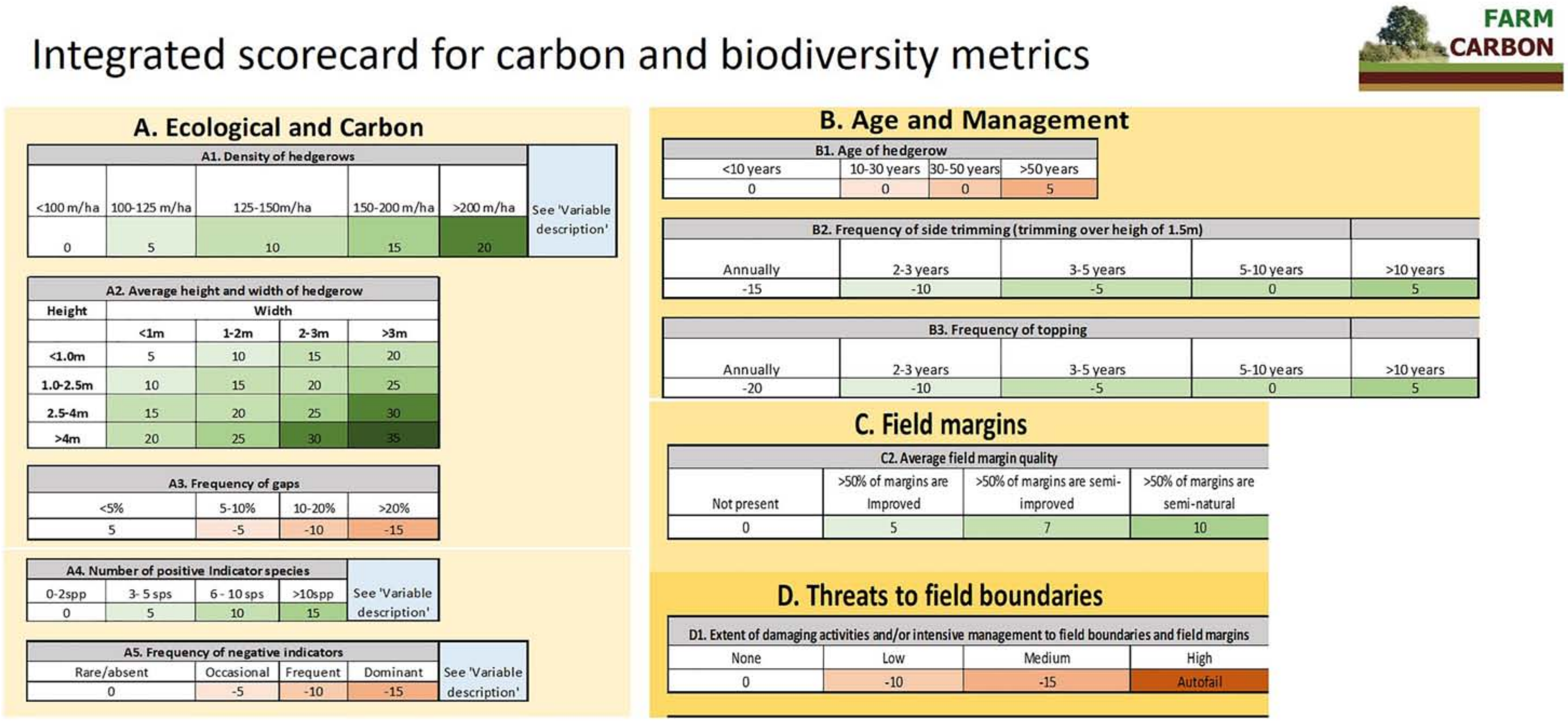
- Age of hedgerow was identified in the Farm-Carbon study as a key driver of C storage; thus, older hedgerows were given a marginal increased score in the integrated scorecard. For ease of assessment, two broad categories were included here, i.e. hedgerows > 50 years and hedgerows < 50 years.
- Intensive management of hedgerows has been identified as a limiting factor for both C storage and biodiversity. Negative scores were included in the scorecard to reflect this. In addition, farmers in the survey identified management as a variable that was relatively easy to assess and thus worth including in rapid assessment scorecards.

6.3.3 Field margins

- Inclusion of a field margin adjacent to a hedgerow can improve the ecological benefits of both the hedgerow and the field margin. There would be potential to revise the weighting associated with field margins (i.e. 10% of overall score) if additional ecosystem services (e.g. buffers for water quality) were considered.

6.3.4 Threats to field boundaries

- Most scorecards include variables relating to damaging activity. Damaging activity is typically damaging for both biodiversity and C sequestration; thus, an autofail is given where there is a high level of damage done to hedgerows. Negative scoring is given for low and medium damage, thus giving farmers some leeway to stop damaging activities (unintentional or intentional) and allow the boundaries to recover but still receive some payment during this time to keep them invested in the process.



Integrated scorecard for carbon and biodiversity metrics

FARM CARBON

A. Ecological and Carbon

A1. Density of hedgerows					
<100 m/ha	100-125 m/ha	125-150m/ha	150-200 m/ha	>200 m/ha	See 'Variable description'
0	5	10	15	20	

A2. Average height and width of hedgerow				
Height	Width			
	<1m	1-2m	2-3m	>3m
<1.0m	5	10	15	20
1.0-2.5m	10	15	20	25
2.5-4m	15	20	25	30
>4m	20	25	30	35

A3. Frequency of gaps			
<5%	5-10%	10-20%	>20%
5	-5	-10	-15

A4. Number of positive Indicator species				
0-2spp	3- 5 sps	6 - 10 sps	>10spp	See 'Variable description'
0	5	10	15	

A5. Frequency of negative indicators				
Rare/absent	Occasional	Frequent	Dominant	See 'Variable description'
0	-5	-10	-15	

B. Age and Management

B1. Age of hedgerow			
<10 years	10-30 years	30-50 years	>50 years
0	0	0	5

B2. Frequency of side trimming (trimming over heigh of 1.5m)				
Annually	2-3 years	3-5 years	5-10 years	>10 years
-15	-10	-5	0	5

B3. Frequency of topping				
Annually	2-3 years	3-5 years	5-10 years	>10 years
-20	-10	-5	0	5

C. Field margins

C2. Average field margin quality			
Not present	>50% of margins are Improved	>50% of margins are semi-improved	>50% of margins are semi-natural
0	5	7	10

D. Threats to field boundaries

D1. Extent of damaging activities and/or intensive management to field boundaries and field margins			
None	Low	Medium	High
0	-10	-15	Autofail

Figure 6.1. Integrated scorecard weighted to account for both biodiversity and C metrics.

7 Conclusions and Recommendations

7.1 Biomass Modelling and National Inventory Reporting

For the first time, direct measurements of hedgerow biomass were taken so that the relationship between measured hedgerow biomass and the corresponding remote measurements could be established. Hedgerows differ in their management, and so two profile types were defined. For these two hedgerow types, two robust models were developed to assess AGB. The approach was successfully applied to a scaled-up approach across two counties utilising the NFI point grid samples. The mean C stocks across all hedgerows were ~57 tC ha^{-1} and 10 tC ha^{-1} for AGB and BGB, respectively. The highest increase in mean biomass CSC was found for emergent hedgerows (3.69 tC ha^{-1} y^{-1}) followed by unmanaged irregular hedgerows (2.87 tC ha^{-1} y^{-1}). The largest biomass losses occur when irregular hedgerows are permanently removed. In the period 2015–2019, hedgerow management resulted in net emissions, despite significant net C increases in unmanaged hedgerows. The approach demonstrated is sufficient to include hedgerows in the GHG inventory. To facilitate the inclusion of hedgerows in the National Inventory Report and annual GHG submissions to the UNFCCC and the European Commission, the availability of repeat survey data is necessary. Remote technologies have been trialled previously (Black *et al*., 2014a; Green *et al*., 2019), with TLS and LiDAR found to be suitable for biomass estimation (Black *et al*., 2014a). The pilot-level study applied in this research and described in Chapter 3 relied on data acquisition from Bluesky Ltd, which had existing series of nationwide remote DEM data. Elsewhere, Denmark included hedgerows in its 2020 inventory submission based on a new model for biomass estimation in hedgerows and small biotopes not included in the forest definition (Nielsen *et al*., 2022). The model was applied to data from LiDAR analysis in 2006 and 2014/2015 (Levin *et al*., 2020), coupled with hedgerow planting data from 1977 to 2020 (Nielsen *et al*., 2022). In their assessment, LiDAR detected differences in volume density depending on whether plots were or were not contained within the NFI, indicating a high level of sensitivity of LiDAR for biomass detection. The availability of LiDAR or other national-level survey data will be required to assess C stock changes over time in an Irish context and could leverage and potentially enhance the work developed in this project.

7.2 Soil Organic Carbon Modelling

Although the SOC data are broadly consistent with SOC stock change of 0.1–3.9 tC ha^{-1} y^{-1} in the literature, this is dependent on hedgerow age, soil type, management regime and previous land use. Based on IPCC (IPCC, 2019) 20- or 50-year steady state assumptions, our reported annualised ΔSOC values are 0.81 or 0.48 (range 0.14–0.8) tC ha^{-1} y^{-1}, respectively. A steady state was not reached by year 50, which may only be relevant when C inputs and management intensity remain constant. Consistent with other literature, the increase in SOC declined with hedgerow age. Both modelled and measured data show that less intensively managed hedgerows sequester more biomass and soil C in the short term, with the biomass C pools and NEE of managed hedgerows resulting in a net emission after 33 years, but with C continuing to be sequestered in the DOM pool. This indicates that the C sequestration potential of hedgerows over the longer term may be overestimated, particularly for intensively managed hedgerows. While implied ΔSOC values are considered significant (Biffi *et al*., 2022) and tier 2 factors for SOC are available, a more intensive soil sampling campaign beyond the scope of this project is required to confirm this.

7.3 Farm-scale Opportunity

The realisation of climate ambitions in Ireland is highly dependent on land use and management decisions made on farm. Although it was beyond the scope of this research to explore the farm-scale climate regulation potential of hedgerows on individual farms, the project still provided an overview of the main farming systems, using generalised data from the National Farm Survey to garner insights into the importance of hedgerows on farms and understand the opportunities offered by them.

At farm scale, the relative potential of hedgerows for contributing to C emissions savings is governed in particular by farming systems. Farming systems in Ireland differ markedly across farm enterprises, from 84 $tCO_2e\,farm^{-1}\,y^{-1}$ for the average arable farm to 568 $tCO_2e\,farm^{-1}\,y^{-1}$ for the average dairy farm. Assuming that 2.73%, 2.93% and 2.67% of dairy, beef and arable farm areas, respectively, are composed of hedgerows, the quantity of C accumulated by regular hedgerows would be equivalent to ~7%, 13% and 43% of dairy, beef and arable farm emissions, respectively. Unmanaged hedgerows could almost double these values, and, by doubling the area of unmanaged hedgerows, the CO_2 sequestered would be equivalent to ~26%, 52% and 172% of dairy, beef and arable farm emissions, respectively.

Adapting management to increase the width and height of hedgerows, along with planting new hedgerows, offers the most potential for climate regulation in hedgerows. This analysis highlights that hedgerows can be an important C store, and the retention and planting of new hedgerows has important mitigation potential at farm scale.

7.4 Integrated Scorecard

Results-based approaches are increasingly important to ensure the impact of agri-environmental schemes. At a practical level, rapid assessment scorecards are increasingly used to assess the implementation of such schemes by different stakeholders. These scorecards are based on easily assessed indicators; however, in general, scorecards are typically focused in favour of one objective, usually biodiversity. This task aimed to develop an integrated scorecard for hedgerows to consider both C storage and biodiversity.

A field assessment at the eight study sites that incorporated a review of six scorecards (Table 5.3) designed for biodiversity assessment, coupled with learning from an anonymous survey of farmers, found that several metrics were universal to all scorecards, but grading differed with respect to hedgerow structural variables that impact both biodiversity and carbon. In addition, hedgerow scores for ecological value varied markedly between scorecards, indicating a need to assess how selected variables are valued. Finally, weighting of scorecards effectively ignored the value of hedgerows for multiple ecosystem services, instead weighting them in favour of one ecosystem service.

An integrated scoring system is proposed with metrics that weight the most relevant variable for biodiversity from existing scorecards with new metrics derived from the Farm-Carbon study and expert opinion. Variables that reflect both ecological and carbon integrity, including density of hedgerows, their height and width, and frequency of gaps, were allocated a much higher weighting (60%) than species indicators that are more associated with ecological quality (15%). Age and management were also identified as key drivers of C storage, with older, less intensively managed hedgerows having potential to be awarded higher scores. Field margins were included.

Additional ecosystem services (e.g. water quality) can be incorporated, with the potential to increase this weighting. Finally, threats to field boundaries are damaging for both biodiversity and C sequestration and so negative scoring is proposed, dependent on the level of damage observed.

An integrated scorecard that incorporates both C sequestration and biodiversity indicators with an integrated weighting, as developed in this project, offers a better fit for recognising the multiple ecosystem services associated with hedgerows, simultaneously, at field level. Similar approaches could be followed if water quality benefits (associated with hedgerows) were included in future iterations of integrated scorecards.

7.5 Future Recommendations

- This research confirms that hedgerow biomass is in decline in Ireland in terms of area because of removals and intensive management. In turn, this means that hedgerow C stock is in decline. Unlike most other EU Member States, Ireland has a sizeable hedgerow stock. As the need to enhance C sinks to mitigate climate change is pressing, reversing this trend is urgently required. This implies greater horizontal integration of policy objectives, requiring a review of existing hedgerow-related policies.
- In addition to complete hedgerow removal, management to reduce the size of irregular profile hedgerows represents an important biomass stock loss.

- The development of management options that sustain C storage potential in the longer term is required. Support for management strategies is required to enhance the sequestration potential of hedgerows in the longer term.
- This work has proposed a methodology for the inclusion of hedgerows as a discrete emission and removal source in national GHG inventory estimates. As demonstrated in this research, developing this capacity can expose the impact of management on C stocks and sequestration in hedgerows. Repeat surveys using techniques such as LiDAR are required. Such data are now becoming available at the national scale (e.g. Bluesky Ltd); however, there are costs associated with the acquisition of these data.
- Although tier 2 factors for SOC are available, a more intensive soil sampling campaign is required to generate data to improve SOC modelling to calibrate hedgerow SOC models. Further research is required to refine the relationship between BGB and AGB C stocks.
- A method to report hedgerow CSCs is proposed for inclusion in the LULUCF inventory estimates. Although the research indicates that the current management of hedgerows may result in net emissions from the biomass pool, alternative, less intensive, hedgerow management can result in significant removals of CO_2 within the LULUCF sector. In particular, policy incentives to allow less intensive management, establishment of new hedges and regeneration of older hedges would increase both the C storage and biodiversity ecosystem service potential.
- Hedgerows represent an important C stock at farm level, and the retention of hedgerows on farms is important for climate and biodiversity objectives. Reducing management intensity and increasing the hedgerow area on farms represents an important opportunity to increase the equivalent CO_2 sequestered. The research also highlighted a positive relationship between biodiversity and C stocks. In the light of growing demands on land, the use of an assessment approach to rapidly score hedgerows for more than one objective is required, and the metrics proposed here could play an important role in current and future results-based payment approaches.

References

Aulino Wann & Associates (2009). *Hedgerow Survey of County Donegal*. The Heritage Council, Kilkenny, Ireland.

Axe, M. (2015). Carbon measurement, prediction and enhancement of the agricultural hedgerow ecotone. PhD Thesis. Coventry University in association with the Royal Agricultural University, Cirencester.

Axe, M.S., Grange, I.D. and Conway, J.S. (2017). Carbon storage in hedge biomass – a case study of actively managed hedged in England. *Agriculture, Ecosystems and Environment* 250: 81–88.

Batjes, N.H. (1996). Total C and N in soils of the world. *European Journal of Soil Science* 47: 151–163.

Biffi, S., Chapman, P.J., Grayson, R.P. and Ziv, G. (2022). Soil carbon sequestration potential of planting hedgerows in agricultural landscapes. *Journal of Environmental Management* 307: 114484.

Black, K., O'Brien, P., Redmond, J., Barrett, F. and Twomey, M. (2009). The extent of peatland afforestation in Ireland. *Irish Forestry* 65: 61–71.

Black, K., Green, S., Mullooley, G. and Poveda, A. (2014a). *Carbon Sequestration by Hedgerows in the Irish Landscape. Towards a National Hedgerow Biomass Inventory for the LULUCF Sector Using LiDAR Remote Sensing. CCRP Report*. Environmental Protection Agency, Wexford, Ireland.

Black, K., Creamer, R.E., Xenakis, G. and Cook, S. (2014b). Improving the YASSO forest soil carbon model using spatial data and geostatisitical approaches. *Geoderma* 232–234: 487–499.

Black, K., Lanigan, G., Ward, M., Kavanagh, I., Ó hUallacháin, D. and O'Sullivan, L. (2022). Biomass carbon stocks and stock changes in managed hedgerows. *Science of the Total Environment* 871: 162073.

Buckley C. and Donnellan, T. (2021). *Teagasc National Farm Survey 2021 Sustainability Report*. Teagasc. Available online: https://www.teagasc.ie/media/website/publications/2022/2021-Sustainability-Report.pdf

Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L. and Bernoux, M. (2018). Revisiting IPCC tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. *Environmental Research Letters* 13. https://doi.org/10.1088/1748-9326/aaeb5f

COFORD, 2021. *All Ireland Roundwood Production Forecast 2021–2040*. COFORD, Dublin, Ireland.

Coleman, K. and Jenkinson, D.S. (1999). RothC-26.3 *A Model for the Turnover of Carbon in Soil: Model Description and User's Guide*. Lawes Agricultural Trust, Harpenden, UK.

COWI, Ecologic Institute and IEEP (2021). *Annexes to Technical Guidance Handbook – Setting Up and Implementing Result-based Carbon Farming Mechanisms in the EU*. COWI, Kongens Lyngby, Denmark.

Crossland, M. (2015). *The Carbon Sequestration Potential of Hedges Managed for Woodfuel*. The Organic Research Centre. Available online: https://www.organicresearchcentre.com/manage/authincludes/article_uploads/project_outputs/TWECOM%20ORC%20Carbon%20report%20v1.0.pdf (accessed 22 November 2023).

CSO (Central Statistics Office) (2021). Census of Agriculture 2020 – preliminary results. Available online: https://www.cso.ie/en/csolatestnews/presspages/2021/censusofagriculture2020-preliminaryresults/ (accessed 9 November 2023).

DAFM (Department of Agriculture, Food and the Marine) (2020). *Forest Statistics Ireland 2020*. Department of Agriculture, Food and the Marine. Available online: https://www.teagasc.ie/media/website/crops/forestry/advice/Forest-Statistics-Ireland-2020.pdf (accessed 9 November 2023).

DEFRA (2007). *Hedgerow Survey Handbook. A Standard Procedure for Local Surveys in the UK*. DEFRA, London, UK.

Drexler, S., Gensior, A. and Don, A. (2021). Carbon sequestration in hedgerow biomass and soil in the temperate climate zone. *Regional Environmental Change* 21: 74. https://doi.org/10.1007/s10113-021-01798-8

Duffy, P., Black, K., Hyde, B., Ryan, A.M. and Ponzi, J. (2022). *National Inventory Report 2022. Greenhouse Gas Emissions 1990–2020. Reported to the United Nations Framework Convention on Climate Change*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland-NIR-2022_Merge_v2..pdf (accessed 12 June 2022).

EC (European Commission) (2016a). Regulation No 525/2013 of the European Parliament and the Council on a Mechanism for Monitoring and Reporting Greenhouse Gas Emissions and Other Information Relevant to Climate Change. Brussels 20.7.2016. Available online: http://ec.europa.eu/transparency/regdoc/rep/10102/2016/EN/SWD-2016-249-F1-EN-MAIN-PART-1.PDF (accessed 29 May 2019).

EC (European Commission) (2016b). Proposal for a Regulation of the European Parliament and of the Council on the Inclusion of Greenhouse Gas Emissions and Removals From Land Use, Land Use Change and Forestry into the 2030 Climate and Energy Framework and Amending Regulation No 525/2013 of the European Parliament and the Council on a Mechanism for Monitoring and Reporting Greenhouse Gas Emissions and Other Information Relevant to Climate Change. Brussels 20.7.2016 COM(2016) 479 final 2016/0230 (COD). Available online: http://eur-lex.europa.eu/resource.html?uri=cellar:9901f171-5017-11e6-89bd-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed 29 May 2019).

EC (European Commission) (2019). The European Green Deal, COM(2019)640, Communication from the Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and the Committee of the Regions. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed 9 November 2023).

EC (European Commission) (2022). Land Use Sector. Available online: https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/land-use-forestry-and-agriculture_en (accessed 12 August 2022).

EU (European Union) (2021). Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02018R0841-20210314&from=EN (accessed 15 August 2022).

Falloon, P., Powlson, D. and Smith, P. (2004). Managing field margins for biodiversity and carbon sequestration: a Great Britain case study. *Soil Use and Management* 20: 240–247.

FAO (Food and Agriculture Organization) (2014). *Agriculture, Forestry, and Other Land Use Emissions by Sources and Removals by Sinks: 1990–2011 Analysis*. Working Paper Series ESS/14–02. Food and Agriculture Organization, Rome. Available online: http://www.fao.org/docrep/019/i3671e/i3671e.pdf (accessed 8 October 2020).

Ford, H., Healey, J.R., Webb, B., Pagella, T.F. and Smith, A.R. (2019). How do hedgerows influence soil organic carbon stock in livestock-grazed pasture? *Soil Use and Management* 35(4): 576–584.

Forest Service (2017). *National Forest Inventory: Republic of Ireland Results Covering the National Forestry Inventory, 2012 to 2017*. Forest Service, Johnstown Castle, Ireland.

Foulkes, N. (2007). *County Mayo Hedgerow Survey Report*. Mayo County Council and The Heritage Council, Ireland.

GoI (Government of Ireland) (2022). *Climate Action Plan 2021*. Available online: https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/ (accessed15 August 2022).

Green, S. (2011). The Irish hedge map V1.0. Available online: https://www.teagasc.ie/media/website/publications/2010/The-Irish-hedge-map-version1_5690.pdf (accessed 9 November 2023).

Green, S., Matin, S., Gharechelou, S., Cawkwell, F. and Black, K. (2019). *BRIAR: Biomass Retrieval in Ireland Using Active Remote Sensing*. Environmental Protection Agency, Johnstown Castle, Ireland.

Holden, N. and Brereton, A.J. (2004). Definition of agroclimatic regions in Ireland using hydro-thermal and crop yield data. *Agricultural and Forest Meteorology* 122: 175–191.

IPCC (Intergovernmental Panel on Climate Change) (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson. C.A., eds). Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme* (Eggleston H.S., Buendia L., Miwa K., Ngara, T. and Tanabe, K., eds). Institute for Global Environment Science, Japan.

IPCC (Intergovernmental Panel on Climate Change) (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Available online: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed 9 November 2023).

Jenkinson, D.S., Harris, H.C., Ryan, J., McNeill, A.M., Pilbeam, C.J. and Coleman, K. (1999). Organic matter turnover in a calcareous clay soil from Syria under a two-course cereal rotation. *Soil Biology and Biochemistry* 31(5): 687–693.

Jones, C.D., Cox, P.M., Essery, R.L.H., Roberts, D.L. and Woodage, M.J. (2003). Strong carbon cycle feedbacks in a climate model with interactive CO_2 and sulphate aerosols. *Geophysical Research Letters* 30(9): 1479.

Jovani-Sancho, A.J., Cummins, T. and Byrne, K. (2021). Soil carbon balance of afforested peatlands in the maritime temperate climatic zone. *Global Change Biology* 27: 3681–3698.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J. and Apps, M.J. (2009). CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* 220(4): 480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma* 123: 1–22.

Lanigan, G., Donnellan, T., Hanrahan, K., Paul, C., Shalloo, L., Krol, D., Forrestal, P., Farrelly, N., O’Brien, D., Ryan, M., Murphy, P., Caslin, B., Spink, J., Finnan, J., Boland, A., Upton, J. and Richards, K. (2019). *An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021-2030*. Teagasc, Johnstown Castle, Ireland.

Larkin, J. (2019). Habitat quantity and quality on intensively managed Irish farmland. PhD Thesis. University College Dublin, Ireland.

Levin, G., Angelidis, I. and Gyldenkærne, S. (2020). *Assessment of Change in Biomass From 2006 to 2014/2015 of Non-forest Woody Vegetation in Denmark. Technical Documentation*. Aarhus University, DCE – Danish Centre for Environment and Energy. Available online: http://dce2.au.dk/pub/TR178.pdf (accessed 9 November 2023).

Li, Z., Kurz, W.A., Apps, M.J. and Beukema S.J. (2003). Belowground dynamics in the carbon budget: recent improvements and implications for the estimation of NPP and NEP. *Canadian Journal of Forest Research* 33: 126–136.

Liski, J., Palosuo, T., Peltoniemi, M. and Sievänen, R. (2005). Carbon and decomposition model YASSO for forest soils. *Ecological Modelling* 189: 168–182.

Mac Elwain, L., Mc Aree, J. and Douglas, I. (2021). *Monaghan Hedgerow Appraisal Survey, 2021. A Decade of Change, Report for Monaghan County Council and the Heritage Council*. Available online: https://monaghan.ie/heritage/wp-content/uploads/sites/13/2021/12/Monaghan_Hedgerow_report_2021.pdf

Matthews, G. (1993). *The Carbon Content of Trees. Technical Paper 4.* Forestry Commission. Available online: https://cdn.forestresearch.gov.uk/1993/09/fctp004.pdf (accessed 9 November 2023).

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Stupak, I., Scott-Bentsen, N., Rasmussen, E., Petersen, S.B., Olsen, T.M. and Hansen, M.G. (2021). *Denmark’s National Inventory Report 2021. Emission Inventories 1990–2019 – Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol*. Aarhus University, DCE – Danish Centre for Environment and Energy, Denmark.

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Stupak, I., Scott-Bentsen, N., Rasmussen, E., Petersen, S.B., Baunbæk, L. and Hansen, M.G. (2022). *Denmark’s National Inventory Report 2022. Emission Inventories 1990–2020 – Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol*. Aarhus University, DCE – Danish Centre for Environment and Energy, Denmark.

Paul, C., Fealy, R., Fenton, O., Lanigan, G., O’Sullivan, L. and Schulte, R.P.O. (2018). Assessing the role of artificially drained agricultural land for climate change mitigation in Ireland. *Environmental Science and Policy* 80: 95–104. https://doi.org/10.1016/j.envsci.2017.11.004

Ruelle, E., Hennessy, D. and Delaby, L. (2018). Development of the Moorepark St Gilles grass growth model (MoSt GG model): a predictive model for grass growth for pasture based systems. *European Journal of Agronomy* 99: 80–91.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., schneider, U., Towprayoon, S., Wattenback, M. and Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B Biological Sciences* 363.

UN (United Nations) (2016). United Nations Sustainable Development Goals. Available online: http://www.un.org/sustainabledevelopment/climatechange/ (accessed 15 August 2022).

UNFCCC (United Nations Framework Convention on Climate Change) (2014). United Nations Framework Convention on Climate Change. Available online: http://unfccc.int/essential_background/convention/items/6036.php (accessed 29 May 2019).

Viaud, V. and Kunnemann, T. (2021). Additional soil organic carbon stocks in hedgerows in crop-livestock areas of western France. *Agriculture, Ecosystems & Environment* 305: 107174.

Abbreviations

AGB	Aboveground biomass
BGB	Belowground biomass
BIO	Microbial biomass
BRIDE	Biodiversity Regeneration in a Dairying Environment
CSC	Carbon stock change
DAFM	Department of Agriculture, Food and the Marine
DEM	Digital elevation model
DM	Dry matter
DOM	Dissolved organic matter
DPM	Decomposable plant material
DSM	Digital surface model
EIP	European Innovative Partnership
Farm PEAT	Farm Payments for Ecology and Agricultural Transitions
GHG	Greenhouse gas
HUM	Humus
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light detection and ranging
LULUCF	Land use, land use change and forestry
LVOS	Lateral view open space
NEE	Net ecosystem exchange
NFI	National Forest Inventory
PV	Projected volume
REAP	Results Based Environment Agri Pilot Programme
RothC	Rothamsted soil carbon
RPM	Resistant plant material
SEM	Surface elevation model
SOC	Soil organic carbon
TIN	Triangulated irregular network
TLS	Terrestrial laser scanning
UAV	Unmanned air vehicle
UNFCCC	United Nations Framework Convention on Climate Change

Appendix 1 List of Equations

A1.1 Description of Field Sampling and Laboratory Analysis (section 2.2)

A1.1.1 Lateral view open space

$$LVOS = \frac{Number\ of\ black\ pixels}{Total\ number\ of\ image\ pixels} \qquad (A1.1)$$

where the LVOS was estimated from the number of black pixels in the side view and the total area is the total number of black and white pixels in the lateral view of the sample zone (Green *et al.*, 2019).

A1.1.2 Dry weight and stone volume

Dry weight and volume of stones calculated based on water displacement recorded in graduated cylinder of known water volume and stone weight:

$$'Real'\ soil\ bulk\ density\ (g/cm^3) = \left[\frac{(NetDW - stones - wood)}{V - Vs - Vw}\right] \qquad (A1.2)$$

where NetDW = GrossDW – bulk density ring weight – aluminium cup weight (g); stones = > 2 mm stones + gravel dry weight (g); wood = > 2 mm wooden debris dry weight (g); V = inner volume of soil bulk density ring = 3.1416 × r^2 × h = 98.17 cm³; Vs = volume of > 2 mm stones = g of STONES/2.50 g cm³ (average density of stones); Vw = volume of > 2 mm wooden debris = g of WOOD/0.8 g cm³ (average density of wood).

A1.2 Biomass to Volume Conversion Factor Development Using Regression Equations (section 2.4)

A1.2.1 Relationship between aboveground biomass and projected volume

The relationship between AGB and PV is assumed to be:

$$AGB_i = a + PV_i \times b \qquad (A1.3)$$

where *a* and *b* are the linear regression intercept and slope coefficients, and *i* is the hedgerow type.

The derived hedge PV is a “dead volume” estimate and does not consider open space beneath the crown and between leaves or branches.

A1.2.2 Lateral view open space adjusted projected volume

Green *et al.* (2019) provided a method to adjust volume (AdjPV) for LVOS ratio:

$$AGB_i = a + AdjPV_i \times b \qquad (A1.4)$$

where

$$AdjPV_i = (PV_i \times LVOS_i) \qquad (A1.5)$$

Equation A1.4 was further modified to include the impact of differences in hedge density based on adsorption of light by the hedge crown:

$$AdjPV_i = \left(PV_i \times LVOS_i \times \frac{1}{\tau_i}\right) \qquad (A1.6)$$

A1.2.3 Belowground biomass equation

BGB models for hedgerow types (i) were developed based on the second-order relationship with AGB, where:

$$LnBGB_i = a + LnAGB_i \times b \qquad (A1.7)$$

A1.3 Scaling to Estimates at County Level (section 3.1)

A1.3.1 National or country-level hedgerow area estimation

The sum of the national or county-level hedgerow area (T_{area}, in ha) is based on the systematic grid representative area of 1 NFI plot (R_{area} = 400 ha) area and the area of hedgerow within the 0.05 ha circular plot (H_{area}). For further details on the NFI, please refer to Chapter 6 of the National Inventory Report (Duffy *et al.*, 2022):

$$T_{area(i,j)} = \sum\left[\frac{H_{area(i,j)}}{0.05} \times 400\right] \qquad (A1.8)$$

A1.3.2 Hedgerow biomass carbon stock calculation for hedgerow class and management type

The sum can be calculated for different hedgerow classes (*i*) and management types (*j*). The total hedgerow biomass C stock (T_{biom}, kgC) per NFI 0.05 ha plot (*p*) is calculated as:

$$T_{biom(p)} = \sum[((AGB+BGB)*0.43)\times H_{area}\times 10000] \quad \text{(A1.9)}$$

H_{area} is expressed in ha, and so a 10,000 multiplier is used to convert ha to m^2.

The total biomass T_{biom} (GgC) for stratum *i* or *j* in the NFI plot area is:

$$T_{biom(i,j)} = \sum[\frac{\frac{T_{biom(p)i,j}}{0.05}\times 400}{1000000}] \quad \text{(A1.10)}$$

Where 0.05 is the plot area and 1,000,000 converts kg to Gg.

A1.4 Comparison of Process-based Models for Soil Organic Carbon (section 4.1)

A1.4.1 Soil organic carbon stocks

SOC stocks were calculated as:

$$\begin{aligned} SOC\left(tC\ ha^{-1}\right) = {} & Soil\ bulk\ density\,(g/cm^{3}) * depth\,(m) \\ & * Soil\ carbon\ carbon\ concentration\ (\%) \\ & * 10{,}000 \end{aligned} \quad \text{(A1.11)}$$

A1.4.2 Annual carbon inputs for process-based models

Directly measured aboveground, belowground, litter inputs and management data were used as model inputs. Additional management data were derived based on survey data over a 5-year period due to a lack of management data (survey information, section 2.5). This approach assumes that AGB stock change losses are due to management. Annual C inputs (annual biomass, litter and management) for different DOM, required to the run YASSO and RothC models, were reconstructed over a 50-year time series.

Annual aboveground biomass and belowground biomass carbon stocks

Annual AGB and BGB stocks (i.e. standing stocks (kg m^{-2})) were modelled using the Chapman–Richards function based on the hedgerow biomass data:

$$AGB_i\ or\ BGB_i = a_i \times exp^{-b_i \times age} \times 1 - exp^{(-b_i \times age)^{c_i - 1}} \quad \text{(A1.12)}$$

Parameters *a*, *b* and *c* were derived using least squares optimisation (Table A1.1), *i* is the hedgerow profile type and *age* is the hedgerow age since establishment.

Annual litter inputs

Annual litter inputs (*L*, $\text{kg m}^{-2}\ \text{y}^{-1}$) were estimated based on a relationship between hedgerow AGB (kg m^{-2}) and

Table A1.1. Solved parameters for AGB, BGB and hedgerow width (equation A1.1)

	Parameter			Model fit	
Component	***a***	***b***	***c***	**r^2**	**RMSE**
Regular hedges					
AGB	205.12	0.0383	3.279	0.91	0.74
BGB	41.408	0.0092	1.714	0.75	2.11
Irregular hedges					
AGB	120.464	0.0279	3.124	0.79	1.13
BGB	18.635	0.02515	1.812	0.89	2.01
Area	140.568	0.000120	1.634	0.96	0.08

RMSE, root mean square error.

Table A1.2. Solved parameters for litter proportion (*PI*, equation A1.13) and deadwood proportion (*PBC*, equation A1.16)

	Parameter		Model fit	
Component	*a*	*b*	r^2	RMSE
Regular hedges				
PI	–0.0021	0.0087	0.51	0.002
PBC	0.2678	–1.132	0.43	0.005
Irregular hedges				
PI	–0.0031	0.0119	0.39	0.006
PBC	0.0055	0.1204	0.12	0.004

RMSE, root mean square error.

the proportion of biomass collected in litter (*PI = litter/AGB*) fall traps:

$$L_{i,tx} = AGB_{i,tx} \times PI_{i,tx} \qquad \text{(A1.13)}$$

and

$$PI_{i,tx} = a_i \times Ln(AGB_{i,tx}) + b_i \qquad \text{(A1.14)}$$

AGB is derived from equation A1.12 for each annual step (*tx*) and hedgerow type (*i*).

Annual fine root (*Fr*, kg m^{-2} y^{-1})) biomass turnover, assumed to be 64.1% of fine root biomass (Li *et al.*, 2003) is based on the estimated of fine root biomass from BGB (Li *et al.*, 2003):

$$Fr_{i,tx} = \left[0.072 + 0.354 \times exp\left(\frac{BGB_{tx}}{16.608}\right)\right] \times 0.641 \qquad \text{(A1.15)}$$

BGB for each annual time step (*tx*) is derived from equation A1.12. The same equation was used for regular and irregular hedges.

Deadwood inputs

Deadwood inputs from hedge cutting at each annual step (cwl_{tx}, kg m^{-2}) for regular hedges and every 5 years for irregular hedges was determined using the relationship between AGB and the proportion of biomass cut (*PBC*) as a result of hedgerow management (Table A1.2):

$$cwl_{i,tx} = AGB_{i,tx} \times PBC_{i,tx} \qquad \text{(A1.16)}$$

and

$$PBC_{i,tx} = a_i \times AGB_{tx}^{b_i} \qquad \text{(A1.17)}$$

Appendix 2 Set-up of the YASSO and RothC Models

A2.1 Set-up of YASSO Runs

The YASSO model describes C stock changes $(\Delta C)_j$ as a function of C inputs from non-woody litter (*nwl*), fine woody litter (*fwl*) or coarse woody litter (*cwl*), allocation of C between compounds and decomposition of compartments at their own rates (*ki*) over unit time. The model is based on basic assumptions of litter/deadwood allocation and decomposition. Input pool compartments each have their own mass loss rate independent of litter origin. Climatic conditions (temperature and precipitation) govern the mass loss rates of the compound groups. The YASSO model used in this study used the previously calibrated parameters for brown earth, lithosols and gley soils, as published by Black *et al*. (2014a). These parameters include values for compound-specific decomposition rates, exposure rates of litter and deadwood to microbial decomposition and initial mass allocation of C between compounds, which are assumed to be the same for hedgerow systems. Non-woody litter (*nwl*) and fine woody litter (*fwl*) were treated as one pool, referred to as *fwl*. This is derived as the sum of annual litter (see equation A1.13) and fine root turnover (see equation A1.15). The *cwl* input pool inputs are derived using equations A1.16 and A1.17. A detailed description of the YASSO model and calibration under Irish conditions is provided by Black *et al*. (2014b) and Liski *et al*. (2005).

A2.2 Set-up of RothC Runs

RothC similarly divides SOC into a number of conceptual carbon pools, with each pool defined by its lability. The model splits soil C input into DPM and RPM, with the ratio depending on the origin of the plant materials. DPM and RPM decompose at different rates into BIO and HUM, thereby releasing CO_2 (Coleman and Jenkinson, 1999). BIO and HUM then decompose at different rates, producing more BIO and HUM CO_2. The partitioning of the products of the decomposition depends on the soil clay content, whereas decomposition rates are modified by temperature, soil moisture and cover vegetation. Initial model spin-ups were performed for grassland and cropland at each site. For cropland, RothC was coupled to the DSSAT crop growth model to generate soil C inputs (Jones *et al*., 2003), while, for grassland, the Moorepark-St Gillies grass growth model (MoST GG) was used to generate above- and belowground inputs (Ruelle *et al*., 2018). Mean 20-year weather data for Met Éireann stations closest to each site were used and spin-ups were performed for 800 years to generate the initial partitioning of SOC between the different C pools for the appropriate land use at each site. C inputs for hedgerows were generated as above for YASSO.

Appendix 3 Limitations

Table A3.1. List of limitations indicated for each site in relation to existing scorecard models

Site code	REAP	BRIDE	Farm PEAT	DAFM	FarmECOS	Hen Harrier
JC1	Invasive species	Gaps	Margin width	Hedge height Hedge richness Hedge gaps Hedge diversity Damaging activity	Hedge height Hedge richness Margin width Margin richness Damaging activity	Gaps
JC2	NA	NA	NA	Margin width	Hedge richness Margin width Margin richness	NA
PC	Invasive species	Topped 1–4 years	NA	Hedge width Hedge height Hedge diversity Margin richness Damaging activities	Hedge width Hedge height Hedge richness Margin richness	NA
DW	NA	NA	Margin width	Hedge width Margin width Hedge richness Hedge diversity	Hedge width Margin width Hedge richness Margin richness	NA
KB1	Hedge height	Topped 1 year Gaps	Hedge height Hedge width Gaps	Hedge richness Hedge diversity Hedge width Hedge height Margin width Gaps	Hedge width Hedge height Hedge richness Margin width Margin richness	Hedge height
KB2	NA	Topped 1 year	Hedge height Hedge width Gaps	Hedge richness Hedge diversity Hedge width Hedge height Margin width Gaps	Hedge width Hedge height Hedge richness Margin width Margin richness	Hedge height Hedge width
OP1	NA	Topped 1 year	Hedge width Hedge height Non-native trees Margin width	Hedge width Hedge richness Hedge richness Hedge diversity	Hedge height Hedge width Hedge richness Margin width Margin richness	Hedge width

Table A3.1. Continued

Site code	REAP	BRIDE	Farm PEAT	DAFM	FarmECOS	Hen Harrier
OP2	NA	Topped 1 year	Hedge width Hedge height Non-native trees	Hedge richness Hedge diversity Hedge width Hedge height Margin width	Hedge height Hedge width Hedge richness Margin width Margin richness	Hedge non-native Non-native trees

NA, not applicable.

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research

Webpages: www.epa.ie/our-services/research/
LinkedIn: www.linkedin.com/showcase/eparesearch/
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie