Assessment of floodplain meadows in Worcestershire and their potential to store soil carbon.

September 2023

Introduction

Worcestershire County Council (WCC) approached the Floodplain Meadows Partnership (FMP) to ask if they could assess the potential for Worcestershire's floodplains to store more carbon than they are doing currently, through restoration from arable land and intensive grassland to species-rich floodplain meadow.

This investigation is therefore an exploratory piece of work to determine whether it is possible to make such an assessment, to gain a broad idea of the amounts of carbon that might be sequestered and to assess the potential costs associated with restoration.

The FMP were approached as they were already collecting soil-carbon data in Worcestershire and Gloucestershire, in 2022, and had already collected similar data from floodplains in the Thames and Ouse catchments. They were therefore in a good position to set data collected in Worcestershire into a wider context.

A summary of the staff from the FMP involved in this work, and their background, can be found in Appendix 1.

The objectives set by Worcestershire County Council were to:

1. Undertake a literature review to:
    - Summarise current understanding of the impact of using grazing livestock in the management of floodplain meadows specifically in relation to balancing carbon emissions and carbon capture/storage.
    - Obtain values for carbon capture rates over time (Year 0 - Year 30) for use in (5)
    - Provide two real world case studies demonstrating the use of any appropriate metric/calculator/code in farm carbon accounting and land-management decision making.

2. Determine typical baseline soil-carbon values for different land-use types within the floodplain, using botanical and soil-carbon data from sources already collected by FMP.

    Land use types that FMP have collected from are:

    - Ancient floodplain meadows.
    - Restored floodplain meadows.
    - Other permanent grassland.
    - Arable.

3. Calculate a predicted soil-carbon baseline for Worcestershire floodplain meadows. Based on an agreed habitat map, calculate the potential current soil-carbon baseline in Worcestershire floodplains, broken down by the four land-use categories listed in (2).

4. Describe and cost management prescriptions for floodplain-meadow restoration to maximise soil-carbon capture and storage.

5. Estimate the amount of soil carbon that may accumulate as a result of habitat restoration.

6. Provide recommendations for next steps, including further data gathering and research and outline where the research might ultimately lead, particularly in terms of informing Worcestershire’s developing Local Nature Recovery Strategy (LNRS).

Literature Review (objective 1)

The literature review can be found in Appendix 2. The key points that are of direct relevance to the following work are:

- Extensive grazing at low stocking rates can increase carbon sequestration. Traditional slow growing stock that are 100% pasture-fed do not require imported feed with its associated carbon cost.
- Whilst the methane released by cattle is a potent greenhouse gas, its effect is short-term compared to that of CO_2, which lasts much longer in the atmosphere. The accepted method of accounting for methane in greenhouse gas budgets has therefore been revised.
- Floodplain meadows continue to accrete soil through flood deposited sediment and may therefore continue to sequester carbon over an indefinite timeframe unlike non floodplain habitats, whose carbon store tends to plateau at an equilibrium amount.
- Carbon is lost more rapidly through a change in land use from permanent grassland to a tilled system, than it can be regained. Therefore, it is important to protect existing stocks.
- Carbon sequestration is correlated with soil age, and some studies suggest it is also correlated with plant diversity.
- Whilst there is information in the literature for other floodplain habitats, there are currently no data that quantify carbon storage and cycling in floodplain meadows specifically.
- There are a range of carbon calculators in use, but these are currently being reviewed by Defra.

Determine typical baseline soil carbon values for different land-use types in the floodplain (objective 2)

Four land-use types within floodplains have been surveyed by the FMP to determine their soil carbon content. They are:

- Ancient floodplain meadows.
- Restored floodplain meadows.
- Other permanent grassland.
- Arable.

Methods used for soil collection and analysis are described in Appendix 3. The numbers of samples used and the locations from which they were collected are summarised in Table 1.

Table 1. Soil samples collected by FMP for the analysis, arranged by river catchment and land use type.

	Severn Vale samples	Thames catchment samples	Ouse samples	Total samples used in analysis
Ancient Meadow	25	89	15	129
Arable	25	24		49
Other permanent grassland	25	N/A		25
Restored Meadow <10 years*	10	24		73 samples used across all restoration ages
Restored Meadow >10 years*	15	24		

*Only samples from restored meadows classed as Lowland Meadows Priority Habitat in condition A or B have been used in the calculations.

The key figures used are organic carbon by weight, calculated from the empirical data, and shown in Table 2 and estimates of dry bulk density. These data are ascribed to three land-use categories: ancient meadows, other permanent grasslands and arable.

Table 2. Amounts of organic carbon in soil broken down by land-use category and soil type expressed as mean values and the 95% confidence interval to reflect the variability within the data.

Land use type	Associated soil series	Amount of organic carbon in the top 50 cm of the soil profile	
		Mean/t ha^{-1}	95% confidence interval/ t ha^{-1}
Ancient meadows	Bishampton	272.7	258.6-287.6
	Brockhurst	267	253.2-281.7
	Fladbury	200.7	190.3-211.8
	Hollington	228.7	216.7-241.2
Other permanent grasslands	Bishampton	181.7	168.7-194.8
	Brockhurst	179	166.2-191.9
	Fladbury	134.8	125.1-144.5
	Hollington	154.3	143.3-165.4
Arable	Bishampton	112.6	103.2-122.0

	Brockhurst	111.8	102.5-121.1
	Fladbury	84.4	77.3-91.4
	Hollington	97.2	89.2-105.3

The choice to use three categories of land-use, rather than the four originally proposed, is because whilst sampled sites could be clearly allocated to the categories for ancient meadow and arable land, the alignment of soil-carbon values to different types of permanent grassland has proven challenging. The available data for intensively managed grasslands in the floodplain are very limited. Our data for where we had understood (based on advice and maps) the grassland to be intensively managed, on closer analysis of the field data, sometimes proved to have relatively low phosphorus availability and relatively diverse swards, suggesting they were not therefore representative of an intensive-grassland category.

Additionally, the soil-carbon values for restored meadows did not prove to be significantly different from other permanent grassland types, leading us to conclude that further data are required to differentiate restored grasslands from intensively farmed ones. Our interpretation of the data is that the history of a field's past management plays a more profound role than its current sward composition in terms of its carbon storage. We have therefore concluded that a single category labelled "Other permanent grassland" is the most valid way of representing the data available. We will continue to gather the management history of sampled sites to allow them to be differentiated in future. Currently therefore, whilst we have carbon-storage values for sites before and after restoration to meadow, we do not have empirical evidence for the rate at which the carbon would be sequestered. We will continue to sample restored meadows of different ages to increase the power of our analysis, but our current data set is too variable in terms of past management histories to derive a statistically sound estimate of sequestration rate.

Published values for bulk-density measurements are not available for every soil series within the study area. Where that is the case, the published value from a closely related series was taken as set out in Appendix 4. The published bulk density values from each horizon were weighted to an estimate of the bulk density at two soil depths: 0 – 20 cm and 20 – 50 cm.

Calculate predicted soil carbon baseline for Worcestershire floodplain meadows (objective 3).

Method

A mapping exercise was undertaken based on geospatial data from the Worcestershire Habitat Inventory (WHI2). The subset of polygons from the WHI2 that overlapped with Flood Zone 2 were extracted and provided by Worcestershire County Council as the starting point for the analysis. This dataset was refined further by extracting all polygons corresponding to UKHabs codes for grassland (g) and arable (c) and then removing the following:

i. Polygons corresponding to UKHabs codes for acid (g1) and calcareous (g2) grasslands
ii. Polygons with values in the 'Label 2' attribute field corresponding to non-grassland or arable habitats[1].
iii. Polygons of undetermined grassland types i.e. with a UKHabs value of "g^…" (174 no.) were reviewed against satellite imagery using Google Earth. Fragments caused by geometry errors and any which were obviously not arable, or grassland habitats were removed.
iv. Polygons <10 m^2 in area (primarily resulting from geometry errors).
v. Polygons 10-20 m^2 were manually reviewed, removing any obvious fragments caused by geometry errors, obviously misclassified areas such as buildings/pylon bases, sections of roads etc.
vi. Overlap analysis was used to identify and remove all polygons with <10 % area within Flood Zone 2. This was to avoid potentially skewing results by including polygons that would contribute large areas of upland soils in the calculations.

Additional attribute data were then added to the refined dataset to allow calculation of soil carbon as follows.

Firstly, soil series attribute data from the National Soil Map[2] was added to each polygon using a one-to-one spatial join. Polygons were then assigned to one of five soil groups with published bulk density data (see Table 2). Sixteen polygons had a soil series of 'lake'. These were manually reviewed and either deleted where unlikely to be practical to manage as meadows (e.g., lake islands, very small strips, areas with poor access etc.) or assigned to the nearest adjacent soil group.

Secondly, all polygons were assigned one of the following three land-use categories, reflecting likely carbon levels:

- Ancient meadows
- Other permanent grasslands
- Arable

Habitat categories within each of the four groups are detailed in Appendix 4, but broadly correspond to: SSSI grasslands (Ancient meadows), permanent grasslands outside SSSIs (Other permanent grasslands) and land subject to recent/regular cultivation (Arable).

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[1] 'Label 2' values removed: Broadleaved woodland, Arable headland or uncultivated strip, Intensively managed orchards, Other unknown terrestrial vegetation, possibly wetland, Unknown terrestrial vegetation, possibly wetland, Built-up areas and gardens, Other unknown terrestrial vegetation, Unknown terrestrial vegetation, Scattered trees, Traditional orchard, Traditional mixed orchard, Traditional pear orchard, Traditional apple orchard, Tall herb and fern (excluding bracken), Tall herb and fern, Tall herb and grasses or 'saum' vegetation, Transport corridors, Transport corridor associated verges only, Quarry, Patchy bracken.

[2] NATMAP Vector dataset (https://www.landis.org.uk/data/nmvector.cfm) & associated Soil series info tabular data (https://www.landis.org.uk/data/ssinfo.cfm)

Mean predicted organic carbon values (t ha^{-1}) for the top 50 cm of soil and their associated upper and lower 95% confidence intervals were added for each combination of soil group and land use type. For each polygon these three values were multiplied by area (ha) to provide a predicted range of baseline organic carbon values (tonnes).

Mean potential organic Carbon values (tonnes) along with their associated upper and lower 95% confidence intervals were calculated for each polygon by multiplying its area (ha) by the minimum and maximum predicted organic carbon values (t ha^{-1}) for the Ancient Meadows land use category and soil group combination.

Results

The distribution of the three land use types across the floodplain of Worcestershire and their estimated baseline Carbon value is shown in Figures 1-3 below.

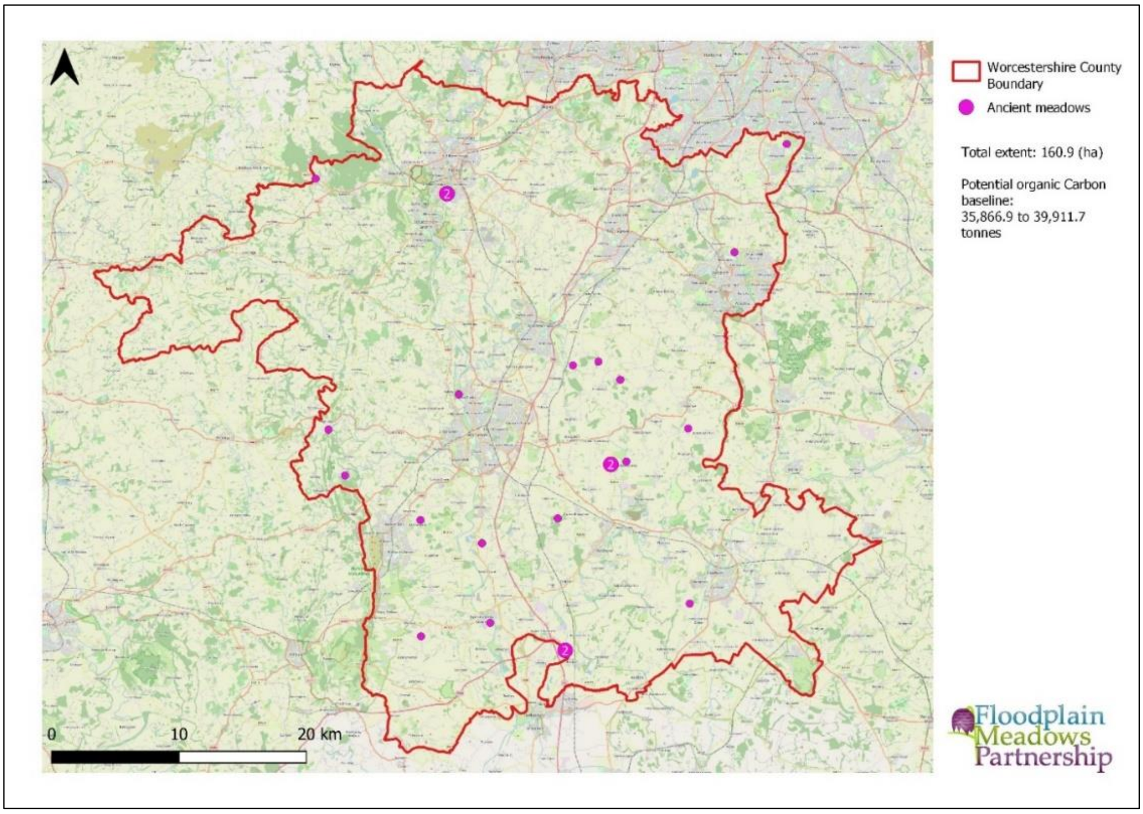


Figure 1. The distribution of ancient floodplain meadows in Worcestershire, extent in ha and potential organic carbon stored.

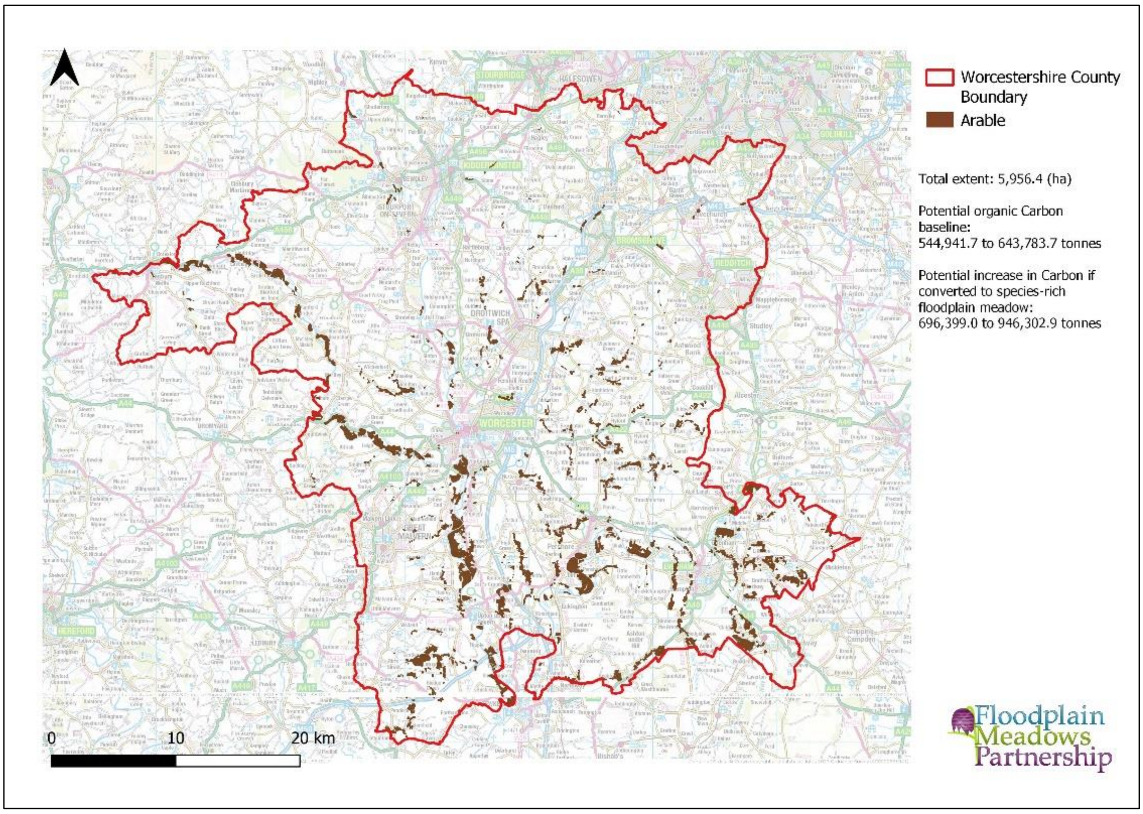


Figure 2. The distribution of arable land in floodplains in Worcestershire, showing extent in ha, current extent of organic carbon, and potential if it were all restored to species rich floodplain meadow.

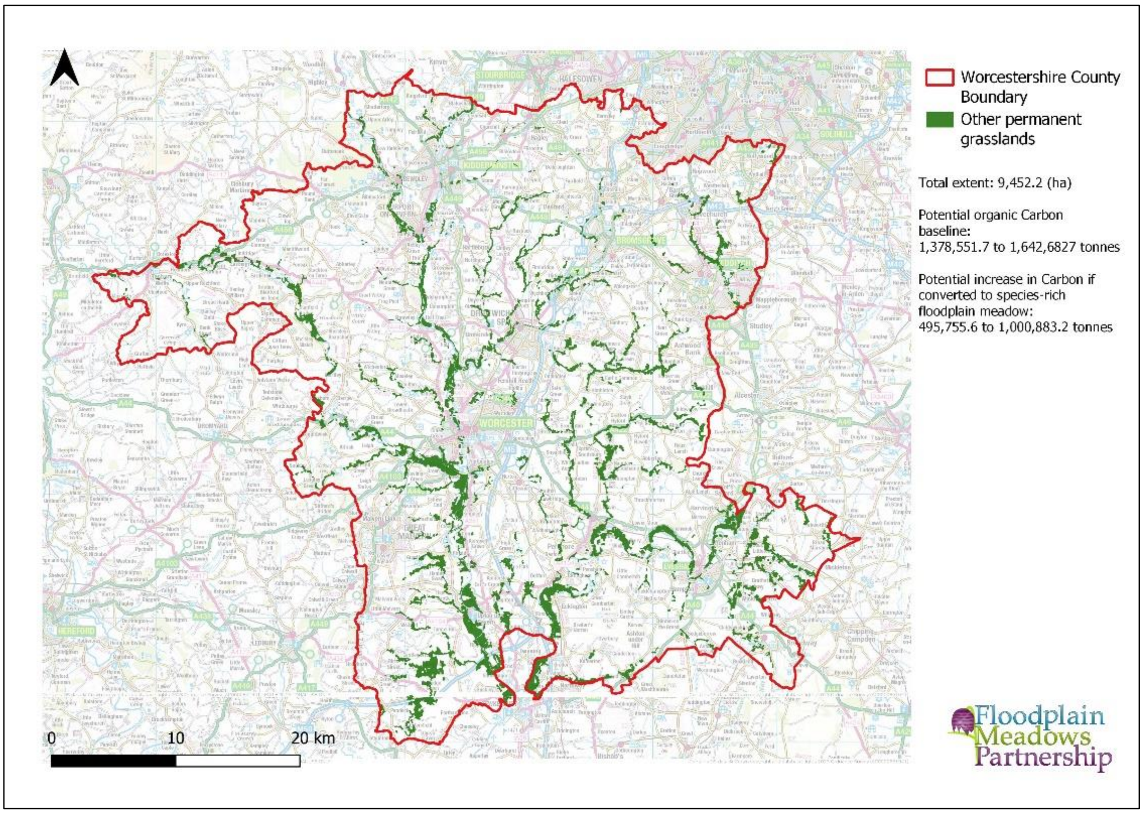


Figure 3. The distribution of other permanent grasslands in floodplains in Worcestershire, showing extent in ha, current extent of organic carbon, and potential if it were all restored to species rich floodplain meadow.

Describe and cost management prescriptions for floodplain meadow restoration to maximise soil carbon capture and storage (objective 4)

Typically, species-rich floodplain meadows require traditional meadow management based around an annual hay cut followed by either a second cut or aftermath grazing in the autumn. There are no additional inputs required, however there is usually a requirement to maintain drainage infrastructure (small scale foot drains to avoid anoxia in the soil surface), to maintain fencing and other livestock management infrastructure, and to deal with any weed issues.

Hay cutting should be undertaken when the hay is ready, at its most nutritious, just before the seed is shed, thus removing the maximum amount of phosphorus. The timing of this is from mid-June onwards, depending on the weather in any one year.

Aftermath grazing usually occurs from August onwards, for a variable length of time, but should end when the soils become too wet to support animals. Second hay cuts are generally taken in September.

Typical management activities are:

- An annual hay cut in late June or early July.
- Livestock grazing to remove the re-growth of grass from August through to February, or until the site becomes too wet.
- Management of hedgerows to prevent encroachment of scrub.
- Maintenance of grazing infrastructure such as fencing, stock handling and drinking points.
- Control of undesirable species such as ragwort, docks, and thistles.
- Maintenance of ditches, gutters, and surface drains.

These are the activities required to ensure that the most nutritious hay crop is removed, and the maximum biodiversity is maintained. These two outcomes are entwined.

The cost of managing a species-rich meadow in a traditional manner with a single cut followed by aftermath grazing is set out in Table 3 below. The total cost is estimated at £392 per hectare per year. Meadows are a productive habitat, supplying both hay and grazing. The financial benefits from these will vary widely depending both on the farming system used and the current market price for stock. It is therefore difficult to give even an indicative figure for the income generated. Over the long term, the direct income is likely to be little more than half the input costs, which explains why meadows have been lost from commercial enterprises across the country. If the manager has entered an agri-environmental scheme, which compensates for the other benefits (biodiversity, soil health, pollination services, flood-risk management, landscape value etc.) then the income and expenditure should more broadly align, although some financial risk will remain.

Persuading landowners and managers to restore meadows on their land will require some financial incentive to overcome the risks perceived. Some capital works and restoration costs will need to be covered to establish a meadow in addition to some incentive to manage it in the long term. The cost of restoration varies considerably depending on the methods used, the machinery available, who is going to undertake the work etc. Even just looking at the costs for green hay spreading, costs vary significantly depending on the cost of the green hay bought from the donor site, the distance to the receptor site, and the amount of site preparation required. We have used figures based on current practitioner experience (our FMP Ambassador network who are regularly involved in costing and delivering floodplain-meadow restoration around the country) and using green hay as a method.

The estimated costs range from £1200/ha up to £1500/ha if distances are longer and donor hay is more expensive.

Table 3. Costs for management sourced from The Farm Management Handbook 2021/22 (Beattie, 2021)

Management activity	**Cost (£/ha)***	**Assumption**
An annual hay cut in late June or early July;	114	a hay yield of 5 t ha^{-1} (200 standard small rectangular bales per hectare)
Livestock grazing to remove the re-growth of grass from August through to early spring, or until the site becomes too wet;	210	aftermath stocking at 3 cattle per hectare; includes direct care of stock, plus maintenance of access, fencing, stock handling and drinking points. Assumes stockman paid at £140/day (gross.)
Management of hedgerows to prevent encroachment of scrub;	18	100 m hedge per hectare trimmed every other year.
Control of weeds or undesirable species such as ragwort, docks, and thistles;	10	Topping prior to seed set every third year
Maintenance of ditches, gutters, and surface drains.	40	200 m ha^{-1} of ditch/grip, cleared every two years,

*2021 rates

Estimate the amount of soil carbon that may accumulate as a result of habitat restoration (objective 5)

The extent of each land-use type has been multiplied by the amount of carbon assumed to be stored to indicate the total current carbon stored in Worcestershire's floodplains (Table 4). This amount has then been compared to the amount found in ancient meadows to calculate the potential increase in soil carbon, if other permanent grasslands and arable fields, were restored to species-rich floodplain meadow. The cost of the restoration of species-rich floodplain meadow using the range of costs set out above are shown for each land use category as a function of its area (Table 4).

Table 4. Current and potential carbon storage in Worcestershire's floodplains, along with the estimated cost of restoration to species-rich floodplain meadow.

Land use type	Current extent (ha) in Worcestershire floodplains	Carbon stored currently in top 50 cm of soil (tonnes)	Potential carbon stored if all converted to species rich floodplain meadows (tonnes)	Potential increase in carbon across Worcestershire (tonnes)	Restoration and capital costs (using a range of £1200 - £1500/ha)
Ancient meadow	161	35,867–39,912	35,867– 39,912	-4045 - 4045	n/a[1]
Other permanent grasslands	9,452	1,378,552–1,642,682	2,138,438 – 2,379,435	495,756–1,000,883	£11,342,640-£14,178,300
Arable	5,956	544,942–643,784	1,340,183 – 1,491,245	696,399 – 946,303	£7,147,680-£8,934,600
Total	**15,570**	**1,959,360 – 2,326,377**	**3,514,487–3,910,591**	**1,188,110–1,951,231**	**£18,490,398-£23,112,998**

[1] The cost of restoration is not applicable to existing old meadows, but the cost of maintaining them should be considered.

References

Beattie, A. (ed.) (2021) *The Farm Management Handbook 2021/22*. SAC Consulting. Melrose. ISBN 978-1-7399808-0-1.

Recommendations (objective 6)

As research on soil-carbon sequestration in floodplains is at an early stage, the outcomes in this report are based on a relatively small dataset and required the use of several assumptions. To develop this work to a point where it can be used for decision making at an appropriate scale the following actions are recommended.

Additional research related to soil carbon and floodplain-meadow restoration:

- Identify and sample grasslands with a long history of intensive management such that an estimate of soil carbon content can be made for this category.
- Follow changes in carbon content and soil bulk density at meadow-restoration sites over time, so that assumptions about the rate of sequestration can be verified.
- Compile a land-use history for each sampled restoration site, so its starting point in terms of soil carbon can be estimated.

Other things that could be considered through the development of the LNRS, using this report as a starting point could be:

Consideration of the economics of carbon sequestration and storage:

- Use the LNRS to build on the existing evidence base to better understand the economic benefits of Worcestershire meadows' natural capital and how to attract private investment.
- Consider how land managers and others might stack payments for carbon storage with other deliverables such as water quality, natural flood management and Biodiversity Net Gain.
- Consider how floodplain meadows can deliver value as part of the farming economic model.

Going beyond carbon:

- Consider linking floodplain-meadow restoration to LNRS delivery for natural processes, species recovery, flooding strategies, catchment planning work, water-retention ability, nutrient neutrality etc.
- Consider if there is capacity to foster the growth of skills and expertise in floodplain-meadow restoration, management, and monitoring locally by providing bespoke support to land managers in Worcestershire wishing to change land use to promote carbon storage
- Consider developing or re-establishing a Worcestershire Meadows Group who could oversee practical aspects of meadow restoration through green hay sharing, seed collection, community growing hubs etc. Such a group could also consider funding sources, community engagement, local food badging and other aspects that would help to market produce resulting from locally produced meat from meadows.

Appendix 1 – Staff profiles

Clare Lawson recently completed a Daphne Jackson Fellowship (funded by NERC) at the Open University investigating soil carbon in floodplain soils. Previously, she has worked on floodplain ecology for a range of clients including NERC, Defra, RSPB, EA, Natural England and Natural Resources Wales. She has extensive experience with respect to project management and scientific writing.

I am a plant ecologist with over twenty years of research work in the areas of habitat restoration, the restoration of biodiversity on ex-arable land and the response of grassland ecosystems to environmental change. My current research focuses on the impact of water-regime and plant community composition on carbon storage in floodplain meadows and the Natural capital of floodplains. I am a Lecturer in Environmental Sciences at the Open University. I have wide-ranging experience in the planning, running, analysis and reporting of large-scale surveys, field and pot experiments and their application. I have a strong publication record in applied ecology, experience in leading research and project management and excellent botanical field survey and plant identification skills.

https://www.open.ac.uk/people/csl237

Emma Rothero has managed the Floodplain Meadows Partnership (FMP) for 10 years and has been instrumental in delivering the range of outreach activities listed. She liaises regularly with stakeholders to ensure delivery of outreach objectives.

The **Floodplain Meadows Partnership Project Manager is Emma Rothero**. Emma has worked in the conservation sector for over 25 years. She has a degree in Freshwater Ecology from Liverpool University and a Masters in Applied Hydrology from the University of Wales, College Cardiff. She then worked for the Environment Agency for 12 years as a Conservation and Recreation and then Biodiversity Officer, providing conservation support to Environment Agency staff as they delivered their duties.

She took up the role of Floodplain Meadows Partnership Outreach Co-Ordinator in 2008, evolving to project manager. This role has included developing the project, securing longer term funding, and building a network of floodplain meadow enthusiasts. She has overseen the management and expansion of the Steering Group and the FMP team and developed projects with local and national partners. She was responsible for the production of the Technical Handbook, the various iterations of the website, training programmes and other publications and materials. She has been responsible for building relationships with stakeholders and is recognised as a Senior Knowledge Exchange Manager at the Open University.

https://www.open.ac.uk/people/ecr58

David Gowing is Professor of Botany at the Open University. He has worked on floodplain-management projects for 25 years and published widely in the academic literature. He has led major research projects for NERC, Defra, and the European Science Foundation; he also works as a consultant ecohydrologist for clients including statutory agencies, local authorities, NGOs, private landowners and commercial operators.

The Project Director is **Professor David Gowing**. He is responsible for overseeing the project and managing the Project Co-Ordinators. He also plays an important role in advocating for floodplain meadows including in discussions with Government.

Professor David Gowing | OU people profiles (open.ac.uk)

Caroline O'Rourke is a Project Officer with the Floodplain Meadows Partnership and has been a floodplain meadows ambassador since 2017, formally joining the Floodplain Meadows Partnership staff in 2022. She has a Postgraduate Diploma in biological recording from the University of Birmingham and is a keen botanist, holding a level 4 Field Identification Skills Certificate (FISC) from the BSBI. She has a background in habitat survey and project management, having worked for several ecological consultancies over 13 years.

She is responsible for management and delivery of several of the projects the FMP are involved in as well as providing support to the FMP survey programme and development of materials such as website re-design.

https://www.open.ac.uk/people/cor75

Appendix 2 – Literature review

Worcestershire County Council assessment of floodplain meadows in Worcestershire and their potential to store soil carbon 2022/23

Literature Review

1. Introduction

Floodplain meadows are a highly biodiverse part of our agricultural landscape, supporting up to 40 plant species per square metre. This high level of botanical diversity is the result of their long-term management via an annual summer hay cut followed by either a second cut or grazing in the autumn. It is essential to take an annual hay harvest as removing soil nutrients from site in the hay lowers levels of nitrogen and phosphorus in the soil and this promotes botanical diversity by preventing tall competitive species from taking over.

The carbon footprint of cattle has received much attention in the drive to reduce emissions to combat climate change. But not all cattle systems are the same and here we discuss the carbon implications of managing floodplain meadows via haymaking and grazing as part of a sustainable pasture-fed livestock system.

2. Carbon implications of managing floodplain meadows via haymaking and livestock

Globally, cattle are reported to produce about 65% of all livestock related GHG emissions and grass-fed systems are responsible for around 20% of that. However, there is wide variation between production systems, such as intensive versus agroecological, and these figures also don't factor in the potential for high levels of carbon sequestration in well-managed grassland soils (Blignaut et al., 2022; Garnett et al., 2017).

Grazing animals remove carbon contained in the plant matter they consume. Much of this is either redeposited via animal waste, which may enter the soil carbon store, or is emitted to the atmosphere as carbon dioxide (CO_2) via respiration or methane (CH_4) via digestion. Only some of the carbon is embedded in the animal's body tissues or milk and removed from site (Garnett et al., 2017) p44. Nitrogen (N) in dung and urine acts to stimulate plant growth and may promote further carbon sequestration through this effect. However, nutrients in animal excreta take a more mobile form and may either be lost through respiration during decomposition by soil organisms or be more readily leached back into water courses than if they were still bound up in plant material (Hogg, 1981; Whitehead, 2009).

Livestock do not add new carbon to the system, but they do affect the cycling of it, locking it into soils and/or releasing it back into the atmosphere (Garnett et al., 2017) p45. The grazing system in place has a strong influence on the net effect of livestock activity. Intensive grazing with high stocking rates on species-poor pasture can deplete soil carbon stocks, whilst non-intensive grazing with low stocking density on species-rich meadows can increase carbon sequestration (Blignaut et al., 2022). The potential size of this effect depends on the soil carbon status when the change in management is introduced (Garnett et al., 2017; Hinshaw & Wohl, 2021; Smith, 2014).

In addition to the loss of soil carbon under intensive grazing systems, the fast-growing breeds of cattle involved necessitate the import of carbon in grain- or soya-based feeds, often produced in areas subject to deforestation, such as the Amazon. The slower-growing breeds of cattle used in sustainable pasture-fed grazing systems are able to thrive on species-rich grazing and hay alone, therefore avoiding potentially significant carbon costs elsewhere (Baker et al., 2023; Soder et al., 2007).

The process of taking the annual hay cut also has a carbon footprint with at least four phases involving tractors for cutting, tedding (turning during drying), baling and transport. This also needs to be considered for a full carbon accounting of meadow management, which we discuss below.

3. System boundaries and assumptions

The carbon cycle can be considered at the scale of an individual meadow (Scope 1), a whole farm system (Scope 2) or at a global scale (Scope 3). This report considers Scope 1 carbon cycling at the individual meadow level.

It is important to recognise that in intensive farming systems, external carbon is imported to the farm through feed containing grain or legumes grown elsewhere with potentially high environmental costs. However, floodplain meadows are usually maintained through low intensity grazing with native breeds of cattle that thrive on an entirely pasture-fed diet, so imported carbon in feed does not need to be considered.

It is also possible to calculate the carbon emissions of livestock, through methane produced during digestion and through their waste. In a pasture-fed system, all the carbon released originates from the plants that have grown in the meadow and so represents a short-term cycle from the atmosphere and soil, through the plant and the animal and back into the atmosphere and soil. A relatively closed loop inside the meadow (Figure 1).

Carbon is exported from the meadow in the hay crop, and this can vary considerably depending on sward density, machinery used and site conditions (Imran et al., 2016; Morissette & Savoie, 2014).

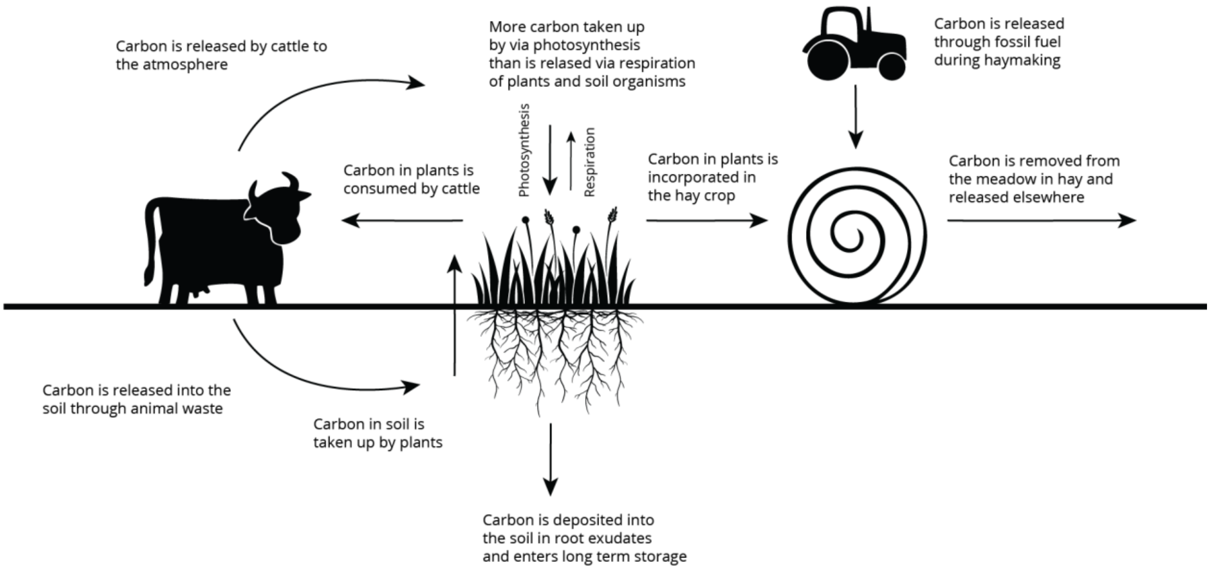


Figure 1: Carbon cycling in a meadow managed through annual haymaking and aftermath grazing in a pasture-fed system.

In this report we will be attempting to quantify the carbon balance of the hay crop and the portion of carbon that moves beyond the closed grazing loop and into the long term, stable carbon stores in the soil.

4. Mechanisms for carbon sequestration in meadows

Firstly, it is important to distinguish between carbon *stocks*, which will depend on previous land use, and carbon *sequestration rates*, which is the rate at which carbon stocks change. Carbon stocks in most systems approach an equilibrium after a period of several decades, so the longevity of active carbon sequestration needs to be taken into consideration. Alluvial meadows are an interesting case however, because they are typically accreting soil from river sediment and therefore may continue to sequester carbon into this new soil as a steady-state process (Blazejewski et al., 2005) (Figure 2).

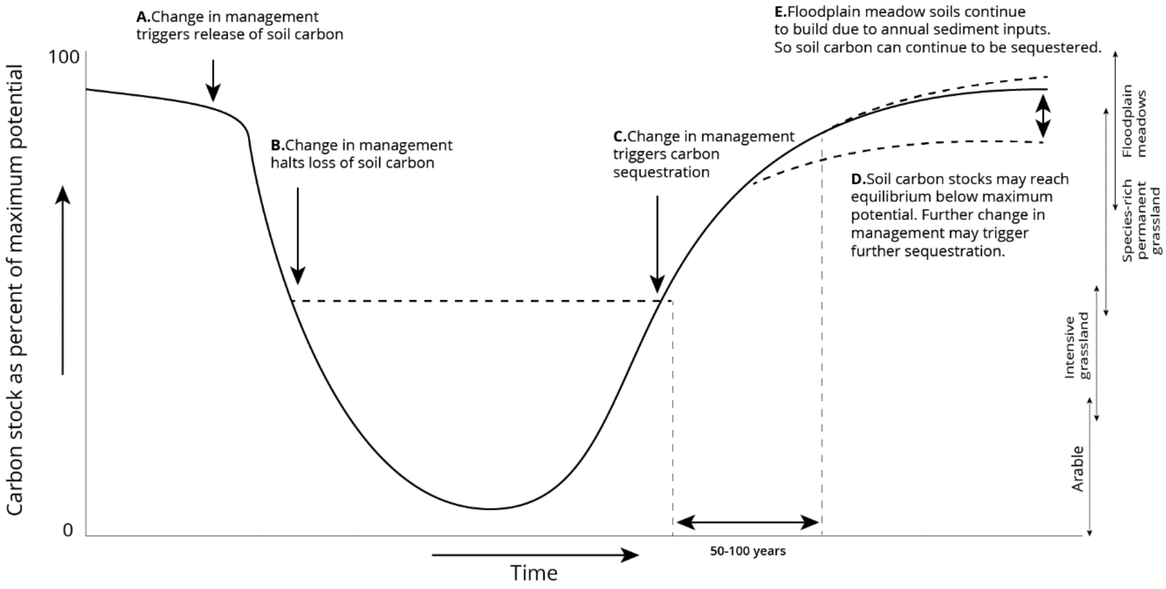


Figure 2: Generalised influence of changes in soil management on soil carbon stocks. A: changes in management such as tillage or fertilisation can prompt carbon loss. The more carbon is present, the quicker it is lost B: Changes such as conversion from conventional farming to organic or no-till systems can halt carbon loss. C: Changes to regenerative systems that result in improvements to biodiversity promote carbon sequestration. With the right interventions a system can move rapidly from B to C. The less carbon you start with, the quicker the initial rate of gain. D: Soils may reach equilibrium at or below maximum carbon potential. If they are below maximum, further improvements in management can promote further sequestration of carbon. E: Floodplain meadows continually build soils due to deposition of flood sediments. As a result, they are able to continue sequestering carbon longer than dry meadows. From (Gregg et al., 2021; Smith, 2014)

Carbon can be lost through poor management or changes to more intensive land use more quickly than it can be built through good management. It is therefore important to protect and maintain existing carbon stocks through appropriate management, as well as working to increase sequestration through the adoption of more regenerative techniques.

Soil type has an influence on carbon storage potential, with well-structured clay soils being able to store more carbon-rich organic matter than sandy soils (Kravchenko & Guber, 2017). The deep humic soils found under permanent floodplain meadows have the potential to store high levels of carbon when managed sensitively through annual haymaking and autumn grazing.

Enriching grasslands through application of fertilisers or planting nitrogen-fixing legumes may increase carbon sequestration by promoting plant growth. However, these methods are only suited to species-poor grasslands and the artificial nutrient enrichment speeds up other nutrient cycles, promoting the release of nitrous oxide and CO_2. These systems are also associated with higher stocking rates in intensive agricultural systems and so any increase in carbon sequestration is often offset by other carbon outputs (Garnett et al., 2017) p46.

The high botanical species-richness found on traditionally managed floodplain meadows is associated with high soil carbon stocks (Gregg et al., 2021; Steinbeiss et al., 2008). This is achieved through long-term management via an annual summer hay cut and either a second cut in the autumn or autumn grazing of the aftermath with a low-stocking density. Changing the land use in floodplains from almost any other use (with the exception of peat-rich wetlands) to floodplain hay meadows can promote carbon sequestration (Cierjacks et al., 2010; Guo & Gifford, 2002). The rate and longevity of the carbon gains will depend on the previous land use, i.e. the location of the site on the carbon curve in Figure 2.

Plants deposit carbon in the soil through roots exudates as well as via dead plant tissues. Carbon-rich compounds produced during photosynthesis are released into the soil profile as exudates that drive biological processes and resource acquisition. Much of this carbon may be released as CO_2 after a period of days, months, or years via biological soil processes but, with appropriate management, a portion of it will enter the long-term carbon stocks that may be stable for centuries or more (Garnett et al., 2017). Analysis of humic compounds (i.e., long-term soil carbon stores) suggest much of it is of fungal origin (Siletti et al., 2017).

Plant growth is driven by a combination of temperature, water, and day length. The most active periods of growth for meadow vegetation occurs during spring through to mid-summer, with a second active growth phase in the autumn after a period of summer dormancy. The physical act of grazing or mowing during the active growth phases prompts a pulse of compensatory regrowth and an associated pulse of carbon-rich root exudates into the soil (Strauss & Agrawal, 1999).

Soil structure and fungal networks are severely damaged by action such as compaction or tillage and can take many decades to form once soil disturbance has ceased. Both fungi and structures such as pore spaces within the soil are important for the stability of carbon stocks, so carbon sequestration is correlated with soil age (Cierjacks et al., 2010; Kravchenko & Guber, 2017; Siletti et al., 2017). Plant species richness is positively associated with higher soil carbon (Norton et al., 2022). Most studies focus on carbon stocks in topsoils, but as much as 60% of the total soil carbon in grasslands may be below this level (Gregg et al., 2021). The particularly deep and diverse rooting structures present in species-rich floodplain meadows helps to build a well-structured soil and maximises the potential for carbon sequestration throughout the soil profile (Bowskill & Tatarenko, 2021).

5. Carbon sequestration rates and fluxes in grassland

Grasslands, as a broad category, are the largest carbon store in the UK and conversion from grassland to arable has resulted in 14.29 Mt CO_2 being released to the atmosphere between 1990 and 2006 (Natural England, 2012). Reversing changes in land management that caused soil carbon to be lost will generally lead to regaining that carbon over time (Guo & Gifford, 2002).

Carbon sequestration potential (Table 2) depends on the condition of the soil at the beginning of restoration or change in management. A highly degraded arable soil has a much higher C potential before reaching equilibrium or saturation than a soil that is already in good condition with high C stocks (Figure 2, Table 1). This legacy effect from previous land use must be considered. Wetlands such as floodplain meadows, when appropriately managed, can sequester carbon at up to “30 to 50 times the rate of forests" according to some researchers (e.g. Hinshaw & Wohl, 2021 describing the results of Tangen and Bansal, 2020, who had worked on Prairie Pothole systems).

Moinet et al (2023) highlight that carbon saturation in soils is not routinely considered in calculations of global soil-carbon sequestration potential (Moinet et al., 2023). Little carbon is accumulated after about 50 years (Table, 2012) and carbon equilibrium may be reached after about 100 years (Cierjacks et al., 2010). Sustained long-term management is required to maintain carbon stocks in the ground and avoid the carbon simply being recycled back to the atmosphere (Garnett et al., 2017; Smith, 2014). Sequestration can be high during the initial years after restoration, gradually declining over the following decades. Changes in the rate of sequestration may be influenced through changes in management some decades past as well as by recent and planned interventions.

Carbon equilibrium may be achieved at or below full saturation, so further alterations in management or natural conditions can be significant in boosting sequestration towards maximum potential. Regular inputs of flood sediments means that floodplain meadows continue to build soils at a rate of around 0.5 mm yr^{-1}, though this figure will vary depending on conditions in the catchment (Craft *et al*., 2018). This means that they can continue to sequester carbon and may never reach a true equilibrium in the way that dry meadows do.

Table 1: Carbon stocks in different land use types (Gregg et al., 2021)

Land use	Soil carbon t C ha^{-1}	Soil depth cm
Acid grassland	87	15
Calcareous grassland	69	15
Neutral grassland	60	15
Improved grassland	130 72-204	100 30
Arable	120 28-88	100 30
Extensive management – relatively high plant diversity and conservation status, typically receives less than 25 kg N ha^{-1} y^{-1}, and have been managed in traditional, low intensity manner for many decades	413.8	100
Intermediate management – typical inputs of 25–50 kg N ha^{-1} y^{-1}, and intermediate levels of plant diversity, grazing and cutting	446.2	100
Intensive management – low plant diversity of mainly MG6 and MG7 NVC communities, typically receive > 100 kg N ha^{-1} y^{-1}. Have been under higher grazing pressure and more frequent cutting for silage since the 1950's	403.0	100

Table 2: Carbon sequestration rates in different land use types.

Vegetation type	**Sequestration t C ha^{-1} yr^{-1}**	**Ref**
Mean across various	0.5	(Garnett et al., 2017) p64
Temperate grasslands – improved mgt of	0.22	(Smith, 2014; Table, 2012)
Permanent grassland, with or without animals on it	0.24	NT *What's Your Beef?* via (Table, 2012)
Permanent grassland	0.24	(Janssens et al., 2005; Table, 2012)

Grassland – first 20 yrs after conversion from conventional to organic	0.42	NT *What's Your Beef?* via (Table, 2012)
Arable – first 20 yrs after conversion from conventional to organic	0.55	NT *What's Your Beef?* via (Table, 2012)
Floodplain wetlands, CZ	0.14	(Craft et al., 2018)
Depressional wetlands, US	0.19	(Craft et al., 2018)
Floodplains of 6 rivers in SW England	0.7-1.1	(Hinshaw & Wohl, 2021; Sutfin et al., 2016)
Rhine floodplain, Germany	0.03-0.25	(Hinshaw & Wohl, 2021)
Danube floodplain, Austria	2.9	(Hinshaw & Wohl, 2021)
Ebro floodplain, Spain	1.4-3	(Hinshaw & Wohl, 2021)
Arable reversion to low input grassland	0.43	(Gregg et al., 2021)

Myrgiotis *et al* (2022) found that cut grasslands were a weaker C-sink than grazed fields when considering all managed grassland in Great Britain. Drought also reduced C-sequestration (Myrgiotis et al., 2022). However, traditionally managed species-rich floodplain meadows have a much greater ability to store carbon than dry grasslands, due to their depth of well-structured soil and are also more drought-resilient than species-poor grasslands.

Carbon-nitrogen interactions may limit C sequestration potential in N-limited soils (Garnett et al., 2017) p43. Functioning floodplain meadows (i.e., connected to their river and receiving seasonal floodwaters) receive N inputs from flood sediments, atmospheric deposition and nitrogen-fixation by a range of legume species and so are less likely to be N-limited compared to other types of grassland.

Methane is a potent greenhouse gas and a third of all anthropogenic methane is emitted by cattle via digestive processes, with a substantial amount also released from wet soils (van den Pol-Van Dasselaar et al., 1999). However, it is short-lived in the atmosphere so cannot be compared directly to CO_2 which has a very long lifespan in the atmosphere (Allen et al., 2022). Taking this into account, cattle can represent a carbon sink in a stable herd living on land under good land management (Blignaut et al., 2022; Garnett et al., 2017). In addition, many of the broad-leaved species common to floodplain meadows contain a range of plant chemicals, such as condensed tannins, that act to reduce methane production during digestion by ruminant livestock (French, 2017; French et al., 2018; Naumann et al., 2017; Waghorn, 2008).

Nitrous oxide (N_2O) is a potent and long-lived greenhouse gas emitted by livestock via their excreta (Garnett et al., 2017) p71. However, N_2O emissions have been found to be much lower in grasslands containing legumes than in intensive agricultural grasslands consisting of few, high-sugar grass species (McAuliffe et al., 2020). In a grass-fed system, grazing by livestock promotes nitrogen cycling but doesn't add any new nitrogen to the system. In fact, it creates N losses by converting N that is bound up in plant matter to more mobile forms of N that may be lost via leaching or released to the atmosphere (Hogg, 1981; Whitehead, 2009).

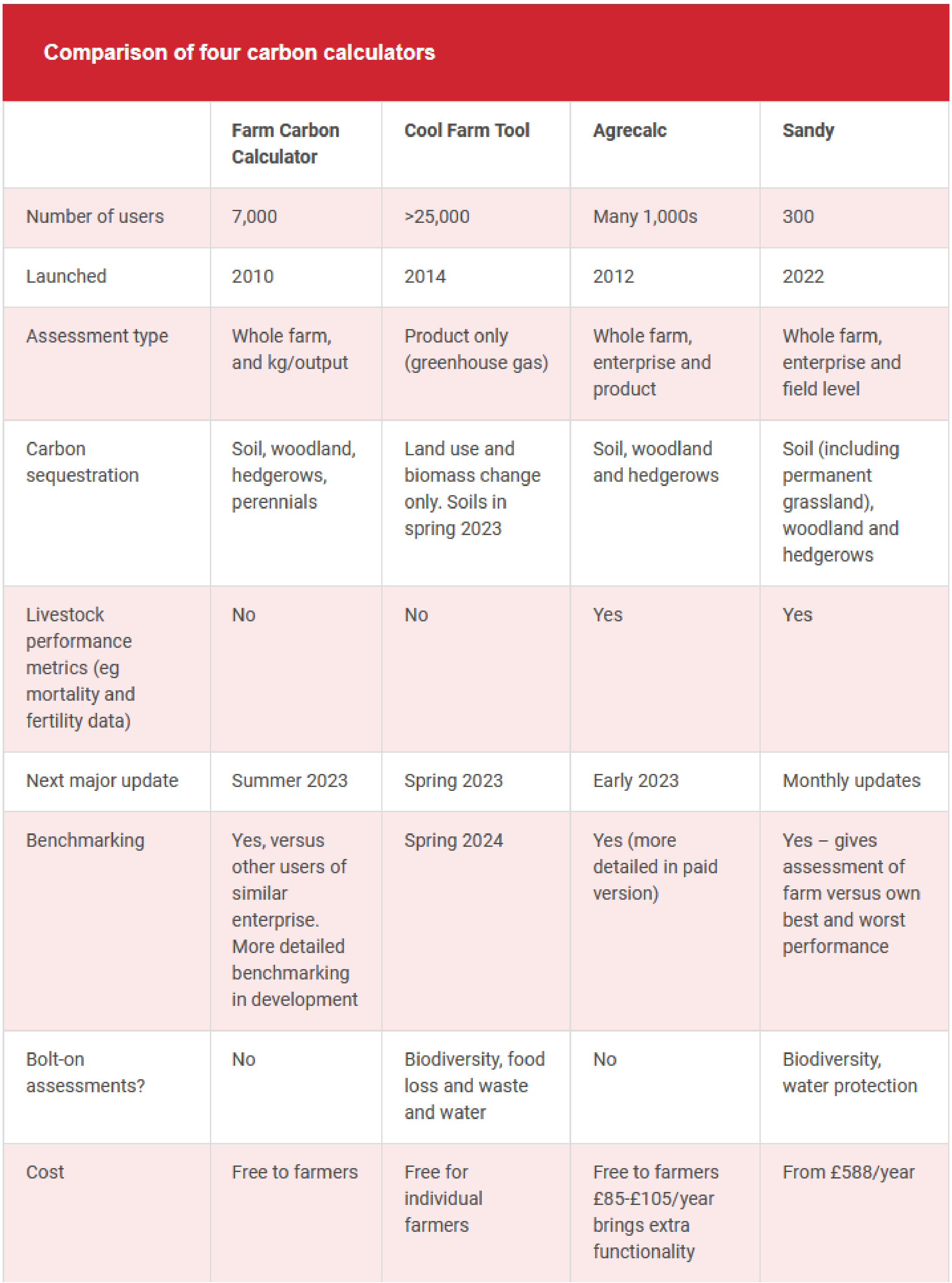
Haymaking is essential to maintaining species-rich meadows, but the influence of mowing as opposed to grazing has rarely been examined (Gregg et al., 2021). Estimates for the carbon footprint of hay harvesting vary widely from 4.77 to 14.2 kg C ha^{-1}, depending on the sward density and machinery used. These estimates are mainly based on high yielding commercial crops. Floodplain meadows yielding 2.5 to t ha^{-1} are likely to be towards to the lower end of this range, which we estimate to be approximately 2 kg C per tonne of hay produced (Imran et al., 2016; Morissette & Savoie, 2014).

Sousanna et al (2007) calculated a greenhouse gas (GHG) balance across a range of grassland types in Europe, concluding that the balance was effectively zero when emissions both on- an off- site from cattle were deducted from sequestration rates (Soussana et al., 2007). Chang et al (2021) also show that, on a global scale, the emissions from cattle in sparsely grazed and natural grasslands cancels out the climate cooling benefits of the soil organic carbon sink (Chang et al., 2021).
As we have discussed in this report, healthy grassland soils under good management can provide a net carbon sink (Blignaut et al., 2022). In addition, floodplain meadows are unique amongst grasslands in their capacity, under the right management regime, to continue sequestering carbon in the long term whilst also providing a valuable hay crop and autumn grazing land.

6. Farm carbon calculators

There is much attention on the range of carbon calculators available and the differences in the way they calculate results. Here we list five commonly used farm carbon calculators. Four of these were compared in an article by Farmers Weekly in October 2022 (Figure 3).

- Cool Farm Tool https://coolfarmtool.org/coolfarmtool/greenhouse-gases/
- Farm Carbon Toolkit https://calculator.farmcarbontoolkit.org.uk/
- Agrecalc https://www.agrecalc.com/
- Sandy https://www.trinityagtech.com/
- Solagro https://solagro.com/works-and-products/outils/carbon-calculator



Comparison of four carbon calculators

	Farm Carbon Calculator	Cool Farm Tool	Agrecalc	Sandy
Number of users	7,000	>25,000	Many 1,000s	300
Launched	2010	2014	2012	2022
Assessment type	Whole farm, and kg/output	Product only (greenhouse gas)	Whole farm, enterprise and product	Whole farm, enterprise and field level
Carbon sequestration	Soil, woodland, hedgerows, perennials	Land use and biomass change only. Soils in spring 2023	Soil, woodland and hedgerows	Soil (including permanent grassland), woodland and hedgerows
Livestock performance metrics (eg mortality and fertility data)	No	No	Yes	Yes
Next major update	Summer 2023	Spring 2023	Early 2023	Monthly updates
Benchmarking	Yes, versus other users of similar enterprise. More detailed benchmarking in development	Spring 2024	Yes (more detailed in paid version)	Yes – gives assessment of farm versus own best and worst performance
Bolt-on assessments?	No	Biodiversity, food loss and waste and water	No	Biodiversity, water protection
Cost	Free to farmers	Free for individual farmers	Free to farmers £85-£105/year brings extra functionality	From £588/year

Figure 3: Comparison of four carbon calculators reviewed in Farmers Weekly 22/10/2022 (Farmers Weekly, 2022)

We are aware of two reports currently underway to bring clarity to the comparability of farm carbon calculators:

- A Defra-funded project is being carried out by ADAS to compare models aimed at finding out how much estimates vary between calculators. The report due out June 2023 (Farmers Weekly, 2022).

- The Wildlife Trusts have commissioned research to review livestock emissions in conservation grazing systems as opposed to commercial grazing systems (The Wildlife Trusts, 2022).

7. Case Studies

- AHDB on Farm Carbon Toolkit https://ahdb.org.uk/farm-excellence/Coton-Wood-Farm/calculating-and-reducing-your-carbon-footprint

8. Limitations

Few studies have examined the carbon sequestration potential of wetlands (Beillouin et al., 2022). Studies that examine semi-natural grasslands tend to focus on acid, calcareous and neutral grassland (Gregg et al., 2021). Haymaking is essential to the management of species-rich meadows but the influence of this on carbon cycling has received little attention (Gregg et al., 2021). Floodplain meadows are a category of wet neutral lowland grassland with important differences in nutrient and carbon cycling compared to other grassland types. The authors of this report are not aware of any studies pertaining specifically to carbon storage and cycling in floodplain meadows (Beillouin et al., 2022). Ongoing work by the Floodplain Meadows Partnership is seeking to fill this gap.

9. Conclusions and recommendations

Conservation strategies designed to maximise the potential for carbon sequestration and long-term storage should incorporate the restoration and sustained management of traditional floodplain meadows (Cierjacks et al., 2010).

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Appendix 3 – Soil sampling and analysis methods

Sampling of soils was conducted at five different locations within each field to measure total carbon, inorganic carbon, pH and available phosphorus. At each location, samples were collected from five holes measuring 5 cm in diameter using a Dutch auger. Soil was sampled from four depths within each hole (0-10, 10-20, 20-35 & 35-50 cm).
An undisturbed soil core was taken at each of the five locations using a 5 cm diameter steel ring to measure bulk density.

A detailed botanical survey, recording all plant species in a 1 x 1 metre sample of vegetation was also completed at each soil sampling location.

Soil groupings for Organic Carbon calculations.

Soil series	Associate soil series literature values used
0572t BISHAMPTON	Bishampton
0411a EVESHAM	Brockhurst
0411b EVESHAM	
0551a BRIDGNORTH	
0551d NEWPORT	
0551g NEWPORT	
0571b BROMYARD	
0571p ESCRICK	
0572a YELD	
0572b MIDDLETON	
0572c HODNET	
0572f WHIMPLE	
0572h OXPASTURE	
0572m SALWICK	
0631b DELAMERE	
0711a STANWAY	
0711b BROCKHURST	
0711c BROCKHURST	
0711f WICKHAM	
0711n CLIFTON	
0712b DENCHWORTH	
0714b OAK	
0821b BLACKWOOD	
0831c WIGTON MOOR	
431 WORCESTER	
543 ARROW	
0511h BADSEY	Fladbury

0541b BROMSGROVE	
0541c EARDISTON	
0541e CREDITON	
0541f RIVINGTON	
0541g RIVINGTON	
0541l BARTON	
0541r WICK	
0813b FLADBURY	
0813c FLADBURY	
0813e COMPTON	
0561a WHARFE	Hollington
0561c ALUN	
0561d LUGWARDINE	
0811b CONWAY	
0811c HOLLINGTON	

Appendix 4: Classification of WHI2 habitat categories to broad land use types

Land use category	Description	WHI2 ‘Label2’ value	WHI2 ‘UKHabs ’ value
Ancient meadows	Historic species-rich meadows only.	SSSI Meadows with MG4/MG5/MG8 on citation.	N/A
Arable	All categories likely to mean recent or regular cultivation.	Arable and horticulture	c1
			c1 20
			c1 20 33 37
			c1 33 36
			c1 33 37
			c1a
		Arable field margins	c1a
		Bare ground	g^ or w^ or h^ or f^ or c^ or u^ or s^ or r^
		Cereal crops	c1c
		Freshly ploughed	c^
		Grass and grass-clover leys	c1b
		Other non-cereal crops including woody crops	c1d8
		Whole field fallow	c^
			c^ 20
		Non-cereal crops	c1d
			c1d c1a6
		Non-cereal crops including woody crops	c1d
Other permanent grasslands	All permanent neutral grasslands outside of SSSIs.	Restoration sites of PHI quality from FMP inventory.	N/A
		Non SSSI sites with confirmed MG4 or MG8 from FMP inventory.	N/A
		Lowland hay meadows	g3a5 65 119 137
		Lowland hay meadows (Alopecurus pratensis, Sanguisorba officinalis)	g3a5
			g3a5 119
		Lowland meadow	g3a
			g3a 119
		Lowland meadows	g3a
			g3a 11
			g3a 119
			g3a 59 60 119
		Lowland meadows and pastures	g3a
			g3a 119
			g3a 33 37
			g3a 119
			g3a 20 119
			g3a 33 36 119
			g3a 33 36 37

Other permanent grasslands			g3a 33 37
		MG5 Lowland Neutral meadows and pastures	g3a
			g3a 119
		Grassland, possibly improved	g
			g 119
		Grassland, possibly unimproved	c^
			c1
			g
			g 119
			g 119
			g 20
			g 20 119
			g 20 33 37
			g 20 33 37 119
			g 33 36
			g 33 37
			g 33 37 119
			g^ or w^ 21
			g3
			g3 1011 119
			g3 119
			g3a 119
			g4
			g4 119
		Grassland, probably improved	c1
			g
			g 119
			g 20
			g 20 119
			g 33 37
			g4
			g4 119
		Grazing marsh pasture	g3
			g3 1011
			g3 1011 119
			g3 119
			g4
			g4 119
		Improved grassland	g 119
			g3
			g3 1011 119
			g3 119
			g4
			g4 119
			g4 20
			g4 20 119

Other permanent grasslands			
		Improved permanent agricultural grassland	g4
			g4 119
		Improved permanent agricultural grassland.	g4
			g4 119
		Modified grassland	g4
			g4 60
			g4 60 119
			g4 64
		Neutral grassland	g
			g3
			g3 1011
			g3 1011 119
			g3 119
			g3 20
			g3 20 119
			g3 33 37
			g3 59
			g4
			g4 119
		Other neutral grassland	g3c
			g3c 11
			g3c 11 119
			g3c 119
			g3c 161 191
			g3c 59
			g3c 60
			g3c 64
		Rank neutral grassland	g3c5 119
		Coarse Grassland	g3
			g3 119
		Coarse neutral grassland	g3
			g3 119
		Lowland meadows (categorised as g3 not g3a)	g3
			g3 119

Appendix 5: Data attributes

Attribute	**Description**
Land use	Land use type used for calculating baseline and potential organic Carbon storage
Soil_Group	Broad soil grouping used for calculating baseline and potential organic Carbon storage
AREA_ha	Area of polygon in hectares
Min OC	Minimum predicted baseline organic Carbon value in top 50 cm soil (t ha-1) (lower 95% confidence level)
Mean OC	Mean predicted organic Carbon value in top 50 cm soil (t ha-1)
Max OC	Maximum predicted organic Carbon in top 50 cm soil (t ha-1) (upper 95% confidence level)
Base_C_min	Minimum predicted baseline organic Carbon value (tonnes) in top 50 cm soil (lower 95% confidence level)
Base_C_mea	Mean predicted baseline organic Carbon value (tonnes) in top 50 cm soil
Base_C_max	Maximum predicted baseline organic Carbon value (tonnes) in top 50 cm soil (upper 95% confidence level)
Pot_C_min	Minimum predicted potential organic Carbon value (tonnes) in top 50 cm soil if converted to species-rich floodplain meadow
Pot_C_max	Maximum predicted potential organic Carbon value (tonnes) in top 50 cm soil if converted to species-rich floodplain meadow
Rest_cost	Estimated capital restoration cost (based on £1,350/ha)
Ann_mgmt	Estimated annual management cost (based on £392/ha)
Flood Zone	Area of polygon within Flood Zone 2 (used to filter original dataset)
Flood Zo_1	% of polygon within Flood Zone 2 (used to filter original dataset)
All other fields	Retained from original WHI2 dataset