ARUP

KNEPP NATTERGAL

Knepp Wildland Carbon project

Glossary

Above ground biomass (AGB)
Living vegetation that exists above the surface of the soil.

Allometry
The relationships that exist between the size of an organism and aspects of its physiology, for example, plant growth and carbon sequestration.

Baselining
The establishment of a reference point or baseline, against which future measurements, comparisons and assessments can be made.

Below ground biomass (BGM)
Living vegetation that exists below the surface of the soil.

Carbon credit
A financial instrument that represents one tonne of carbon dioxide equivalent ($1tCO_2e$), which has either been removed from the atmosphere or its emission has been avoided.

Carbon sequestration
The process of capturing and storing greenhouse gases (GHG) from the atmosphere, expressed as carbon dioxide equivalent (CO_2e).

Carbon stock
The quantity of carbon physically stored in a habitat at a given point in time.

Monitoring, reporting and verification (MRV)
Monitoring involves the systematic collection and measurement of data, reporting involves the regular and transparent communication of this data, and verification involves the independent assessment and authentication of this data, including its compliance with reporting standards.

Natural colonisation
The establishment through natural processes of new trees or scrub on land that has not supported woodland cover for a long time, if ever. This contrasts with tree planting and other human-led interventions for establishing new trees and scrub.

Natural regeneration
The establishment through natural processes of new trees or scrub on land that currently supports, or has recently supported, woodland cover. This contrasts with tree planting and other human-led interventions for establishing new trees and scrub.

Nature-based solution
Anything that involves working with nature to address societal challenges, supporting human wellbeing and biodiversity locally. They include the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands; and integration of nature in and around our cities.

Nature restoration
The process of increasing ecosystem function, scale or integrity. Outcomes of nature restoration can include increased biodiversity and bioabundance, as well as enhanced ecosystem services. Nature restoration can be passive or active, management-led and/or process-led and occur over a variety of spatial and temporal scales.

Rewilding
An approach to nature restoration that focuses on the re-instatement of ecological processes (often termed ‘natural processes’), such as seasonal flooding, habitat succession and naturalistic grazing. Rewilding can be characterised as being nature-led but human-enabled, with no predetermined end point.

Terrestrial rewilding
Using a process-led approach to achieve restoration of land-based ecosystems and habitats.

Voluntary carbon markets (VCM)
A type of ecosystem market that facilitates the generation and sale of certified carbon credits between suppliers, brokers and end users.

Executive Summary

The Knepp Wildland Carbon Project was funded following a successful application to the second round of the Natural Environment Investment Readiness Fund (NEIRF) in 2022. Initially, the project set out to produce a carbon protocol for process-led nature restoration – often simply termed 'rewilding' – projects across the UK. However, there are currently too many data gaps in the scientific literature for a market-ready protocol to be created for the types of habitats that emerge in rewilding projects. As a result, the Knepp Wildland Carbon Project evolved to focus on the data gaps that still remain around the carbon sequestration and storage potential of these habitats, using the Knepp Estate as a real-world example from which in situ measurements could be taken.

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The habitats that emerge from process-led nature restoration projects can include grasslands, wetland, scrub, and young woodland, often intermixed throughout a landscape in an ever-evolving dynamic mosaic. For convenience, we refer to these habitat mosaics as 'rewilding habitats' throughout this paper, acknowledging that such ecosystems are specific to lowland Britain and parts of northwest Europe.

By combining analysis of the carbon sequestration and storage occurring within 'rewilding habitats' on Knepp Estate, with analysis of the UK's Voluntary Carbon Market (VCM), the Knepp Wildland Carbon Project coalesced around three objectives:

1. To explore both data and data-acquisition gaps in the carbon sequestration and storage potential of 'rewilding habitats' in the UK, through review of the existing scientific literature and in situ measurement of above and below-ground carbon stocks at Knepp Wildland

2. To understand the potential for generating certified carbon credits from 'rewilding habitats', termed 'rewilding carbon credits', within the context of the UK Voluntary Carbon Market

3. To create a guide, using Boothby Wildland as a case study, that UK nature restoration projects wanting to understand their carbon stocks and potential sequestration can follow; outlining an approach to baselining and monitoring, reporting and verification of carbon sequestration

Overall, this project provided clear evidence of the effectiveness of 'rewilding habitats' as a nature-based solution to both the climate and biodiversity crises, with estimated total (i.e. above and below-ground) carbon sequestration rates of **5.20 tCO_2e ha-1 yr-1*** over ~20 years across formerly arable farmland on Knepp Estate. This estimate is likely to be conservative, as it does not take root biomass into account, and is comparable to the carbon sequestration rates for woodland creation projects in lowland Britain, as estimated by the Woodland Carbon Code's carbon calculator. However, at Knepp, the majority of carbon sequestration occurred below ground, into ex-arable soils, highlighting the importance of this habitat for climate mitigation.

Based on these findings, there is significant potential for 'rewilding carbon credits' to be generated and sold within the UK Voluntary Carbon Market. The biodiversity co-benefits that 'rewilding habitats' deliver could also allow 'rewilding carbon credits' to be sold for a premium. However, the lack of standardised monitoring, reporting and verification (MRV) protocols, the remaining uncertainty around sequestration rates, and carbon pricing within the VCM are currently hindering major investment into 'rewilding carbon credits'.

None of these barriers are insurmountable and if the co-benefits of process-led nature restoration are adequately priced into the cost of 'rewilding carbon credits', then carbon finance could allow rewilding projects to scale rapidly. This should be an ambition for policy-makers and practitioners within the VCM because process-led nature restoration projects have the potential to deliver greater biodiversity uplift than analogous projects that focus on woodland creation through tree planting alone.

Whilst this report and project focusses on process-led rewilding, the data and baselining approach is also compatible with management-led biodiversity and habitat restoration projects.

***tCO_2e ha-1 yr-1**
Tonnes of CO_2 equivalent per hectare per year

01

Introduction

Section 1: Introduction

1.1 Background

The Knepp Wildland Carbon Project is a Natural Environment Investment Readiness Fund (NEIRF) project (Project Reference 2059), which was initiated in September 2022. The project's aim was to fill crucial data gaps in the scientific literature around carbon sequestration in what we term 'rewilding habitats'; these being the dynamic mosaics of natural habitats that emerge during process-led nature restoration. The project's ambition was to explore whether this data, once obtained, could be used to produce a scalable model enabling land managers in the UK to measure, unitise and trade the greenhouse gases sequestered by terrestrial rewilding projects.

However, there are currently too many data gaps in the scientific literature for a high-integrity protocol to be created for the types of habitats that emerge in rewilding projects. As a result, the Knepp Wildland Carbon Project evolved to focus on the data gaps that still remain around the carbon sequestration and storage potential of these habitats, using Knepp Estate as a real-world example from which in situ measurements could be taken.

By combining analysis of the carbon sequestration and storage occurring within 'rewilding habitats' on Knepp Estate with analysis of the UK's VCM, the Knepp Wildland Carbon Project coalesced around three objectives:

Objective 1: Research
To explore remaining data gaps and data acquisition in the carbon sequestration and storage potential of 'rewilding habitats' in the UK, through review of the existing scientific literature and in situ measurement of above and below-ground carbon stocks at Knepp Wildland.

Objective 2: Application
To understand the potential for generating certified carbon credits from 'rewilding habitats' within the context of the UK voluntary carbon market.

Objective 3: Replicability
To create a guide, using Boothby Wildland as a case study, that UK nature restoration projects wanting to understand their carbon stocks and potential sequestration can follow; outlining an approach to baselining and monitoring, reporting and verification of carbon sequestration.

This report explores each of these objectives in turn, initially contextualising rewilding as a form of process-led nature restoration (Section 2) before exploring the data gaps that exist in the literature (Section 3). Section 4 describes the study undertaken at Knepp Wildland to ascertain the carbon sequestration and storage potential of 'rewilding habitats' and their soils, before looking at the applicability of these results for ecosystem markets such as the UK VCM in Section 5.

The report then uses Boothby Wildland to outline how other UK nature restoration projects that want to understand their carbon baseline might do so (Section 6). Finally, in Section 7, several barriers to immediate implementation of such a business model are identified and suggestions made about how these barriers can be overcome. The report concludes with several recommendations for policymakers and other practitioners involved in UK Nature Recovery.

The development of this report, and supporting research, has been funded through the second round of the NEIRF, which is delivered by Defra and the Environment Agency, to support nature projects to attract private investment and publish learnings for other projects to follow. The project has been led by the Knepp Estate, Arup and Nattergal, with project partners including Agricarbon, Treeconomy and Queen Mary University London.

Image 1

Exmoor Ponies in the regenerating scrubland at Knepp, with oak trees growing through bramble thickets.

Photo Credit: Knepp Estate

1.2 Strategic Context

Society's need to address the interlinked climate and biodiversity crises has led to the emergence of 'nature-based solutions' (NbS). These are interventions that involve working with nature to address societal challenges, supporting human well-being and biodiversity locally. NbS include the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands; and integration of nature in and around our cities[2].

At the same time, the effectiveness of process-led nature restoration, often termed 'rewilding', for reversing biodiversity decline has led to the proliferation of nature recovery projects using a process-led approach. However, the climate benefits of such 'rewilding' projects are poorly understood, largely due to a lack of data and studies around the carbon sequestration and storage potential of the dynamic habitat mosaics and soil health recovery that emerge through process-led nature restoration.

As a result, there is a clear need to quantify the effectiveness of 'rewilding' as a NbS to climate change. If robust, high-integrity estimates of 'rewilding habitats' and soil carbon sequestration and storage potential can be made, it could allow process-led nature recovery projects to become ecosystem markets, such as the VCM. This would provide new routes for financing such projects and, potentially, allow them to become an investable proposition for private sector actors, helping this type of project to proliferate and scale.

02
Rewilding

Section 2: Rewilding

Rewilding Definition

Rewilding is an approach to nature restoration that focuses on the re-instatement of ecological processes (often termed ‘natural processes’), such as seasonal flooding, habitat succession and naturalistic grazing. Rewilding can be characterised as being nature-led but human-enabled, with no predetermined end point.

2.1 Overview

Rewilding is both a practical approach to nature restoration, which prioritises the re-instatement of ecological processes, and an overarching philosophy for nature recovery. Ultimately, it aims to create landscapes and functioning ecosystems that require fewer management interventions over time and have increased resilience to environmental and anthropogenic impacts.

Figure 1 below shows the continuum of rewilding in relation to land use change and human modification.

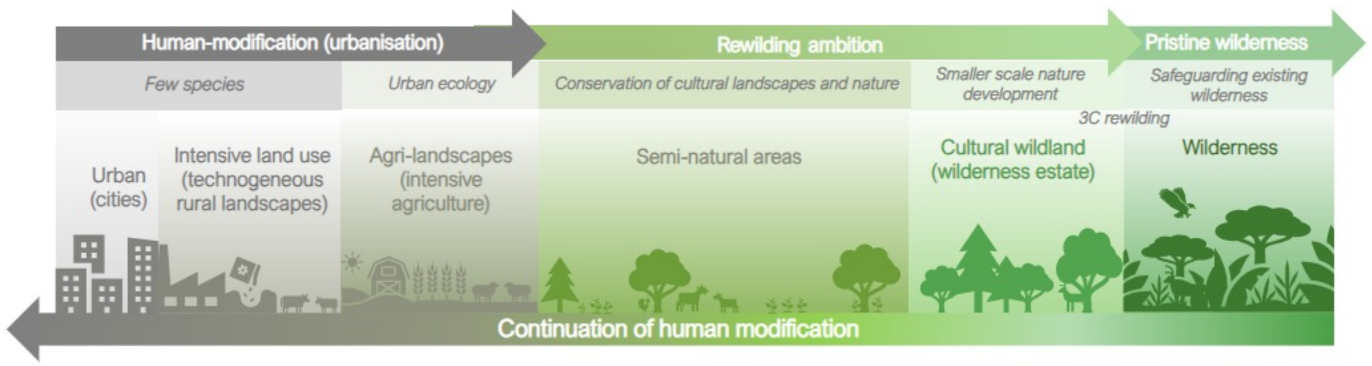


Figure 1
A continuum of rewilding
(Source: Arup, 2023)

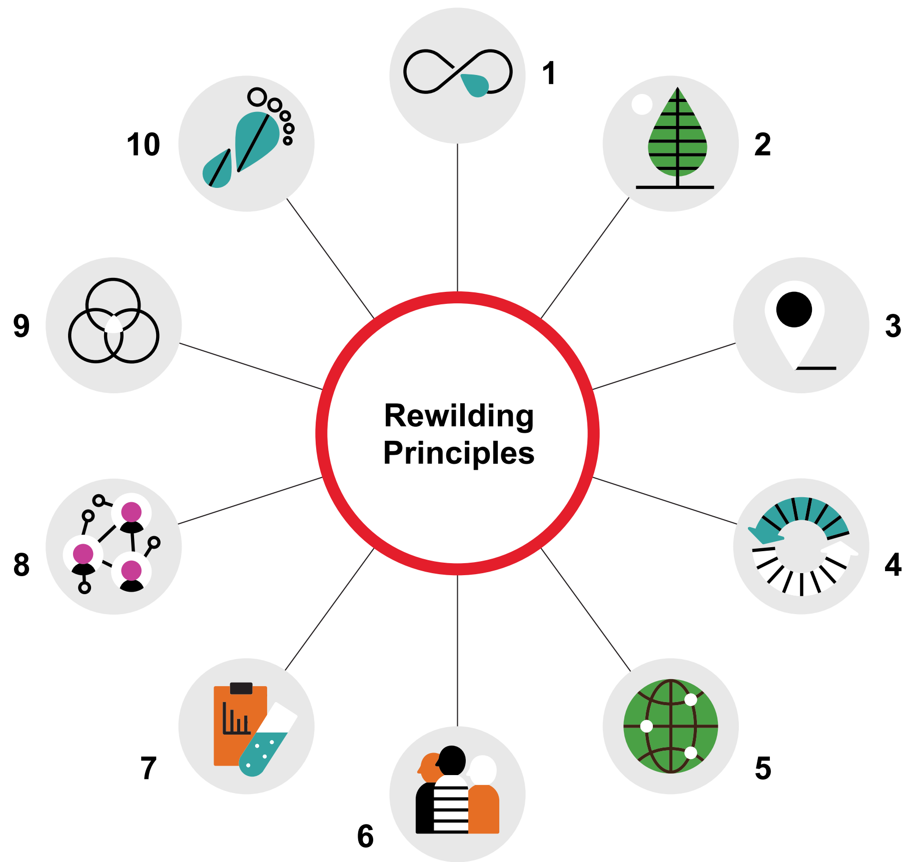
2.2 How to undertake rewilding

There is no ‘one way’ to rewild a landscape. Various approaches can be taken depending on the existing environment, the ecological context, the size of the landholding, neighbouring activities, finances and the ambition of the land manager. However, the International Union for the Conservation of Nature has attempted to define 10 key principles that demarcate rewilding from other approaches to nature restoration[3].

These Rewilding Principles are:

1. Rewilding utilises wildlife to restore trophic interactions.
2. Rewilding employs landscape-scale planning that considers core areas, connectivity and co-existence.
3. Rewilding focuses on the recovery of ecological processes, interactions and conditions based on reference ecosystems.
4. Rewilding recognises that ecosystems are dynamic and constantly changing.
5. Rewilding should anticipate the effects of climate change and where possible act as a tool to mitigate impacts.
6. Rewilding requires local engagement and support.
7. Rewilding is informed by both science and indigenous and local knowledge.
8. Rewilding is adaptive and dependent on monitoring and feedback.
9. Rewilding recognises the intrinsic value of all species and ecosystems.
10. Rewilding requires a paradigm shift in the co-existence of humans and nature.

These principles can be applied to rewilding projects across various scales and at different stages.



Section 2: Rewilding

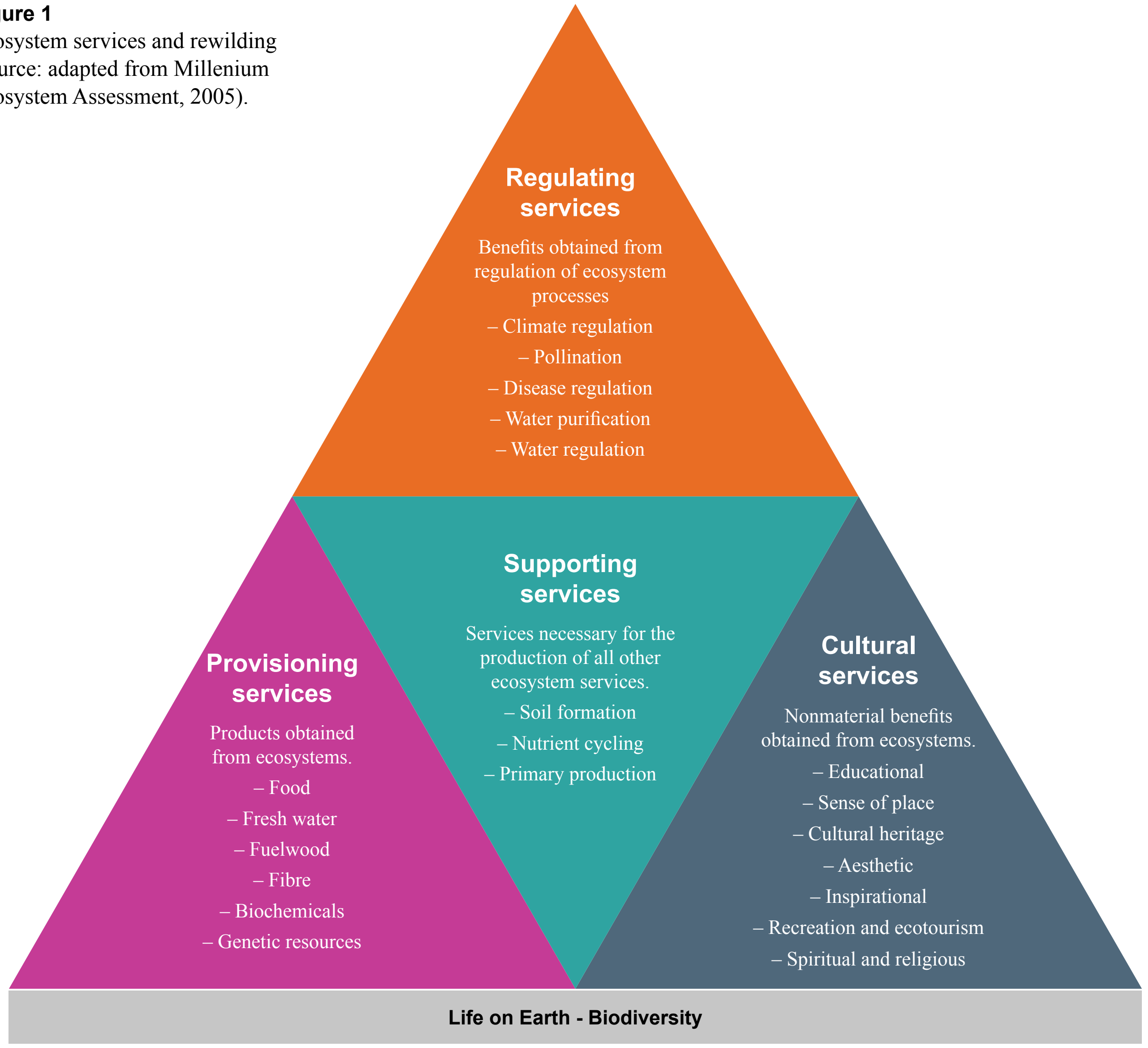
2.3 What benefits does rewilding bring?

As an approach to nature restoration, rewilding can deliver multiple benefits including increased biodiversity and enhanced ecosystem services, such as carbon sequestration and storage, water regulation and soil formation.

Figure 2 illustrates the ecosystem services that can be realised by rewilding initiatives such as those occurring at Knepp Estate.

Ecosystems with functioning natural processes are also more resilient to change, such as the impact of more frequent and extreme weather events. The resilience of our natural habitats is going to be increasingly tested as the impacts of climate change accelerate, with extreme temperatures leading to increasing frequency and severity of natural disasters such as drought, disease, flooding and fires. As such, process-led nature restoration projects have the potential to mitigate some aspects of climate change, while also contributing to restoring nature, enhancing biodiversity, and creating more resilient ecosystems that can better adapt to climate impacts.

Figure 1
Ecosystem services and rewilding (source: adapted from Millenium Ecosystem Assessment, 2005).



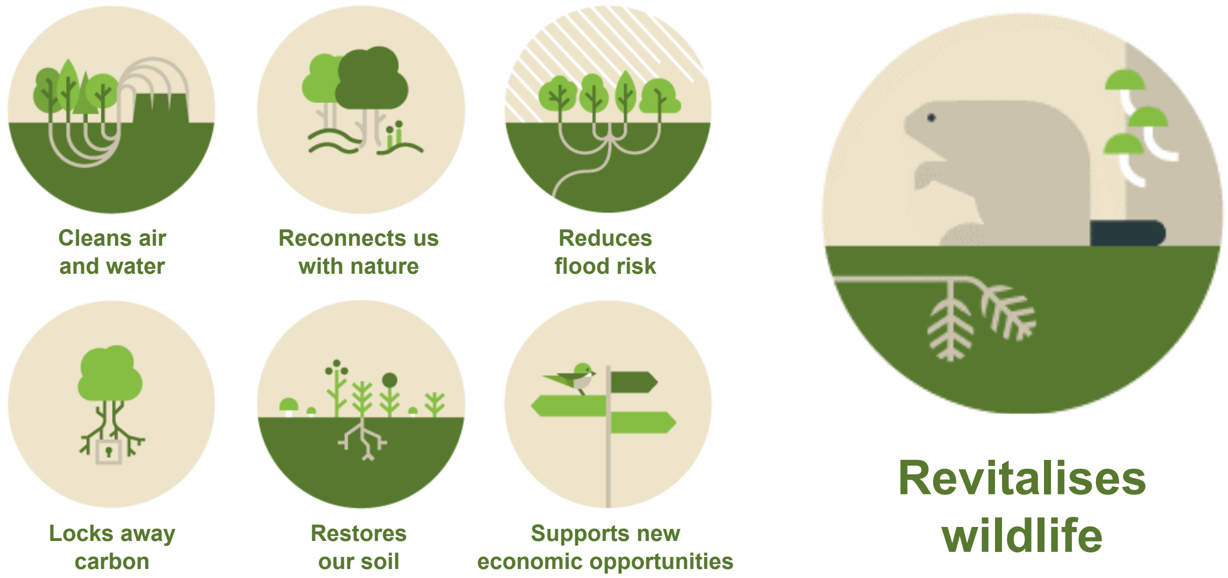


Figure 3
How Rewilding Helps Us
(Source: Rewilding Britain)

Rewilded environments can also create a platform for nature-based economies and activities, such as eco-tourism and recreation. Furthermore, rewilding creates spaces for people to interact with nature, generating health and wellbeing benefits[4].

Section 2: Rewilding

2.4 Rewilding and carbon sequestration

A rewilding project, if planned and implemented effectively, will sequester atmospheric carbon dioxide (CO_2) and store it in biological matter (i.e. soils, scrub and trees) as carbon. All carbon and greenhouse gas figures are converted to carbon dioxide equivalent (CO_2e) to enable and simplify global comparisons (with 1 tonne of carbon converting to 3.67 tonnes of CO_2e).

For terrestrial rewilding projects in lowland Britain, carbon is sequestered both below ground, in biologically recovering soils and the root mass of trees, and above ground, in the woody biomass of trees and scrub. However, the habitats that emerge from process-driven nature restoration are often context specific and mixed across landscapes in dynamic mosaics, which makes measurement challenging.

This, combined with historic attitudes towards habitats such as scrub, means that the knowledge base for carbon sequestration and storage in 'rewilding habitats' is limited, especially in comparison to the woodland habitats that are important for commercial forestry.

However, given the urgency of the biodiversity and climate crises there is a critical need to understand what true nature-based solutions can be scaled and deployed to help our societies halt biodiversity decline and mitigate global heating and adapt to a warming world. In light of this, it is essential that the knowledge base for carbon sequestration and storage in 'rewilding habitats' is rapidly augmented.

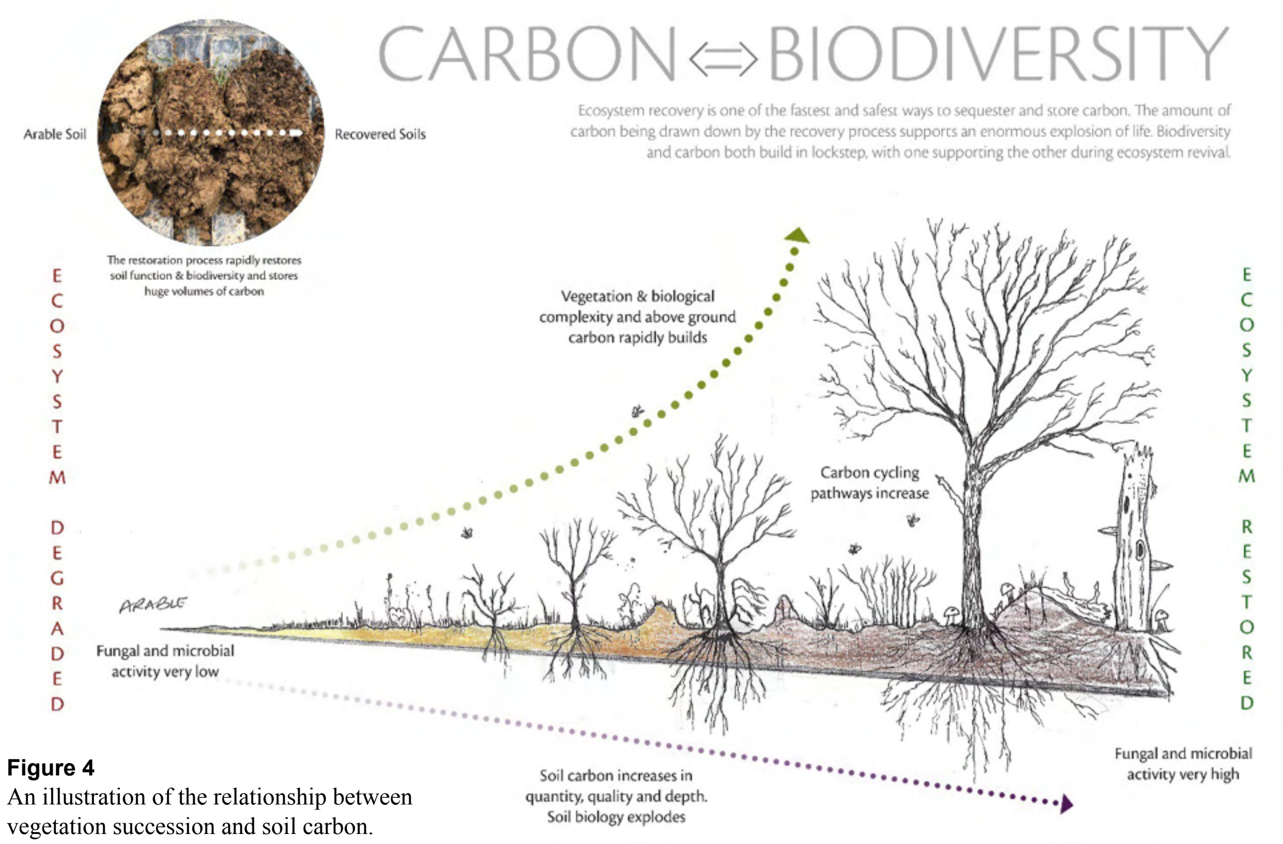


Figure 4
An illustration of the relationship between vegetation succession and soil carbon.
Credit: Digg and Co.

2.5 Delivery of rewilding to date and the potential for the future

Globally, the loss of biodiversity is now seen as an existential crisis of similar magnitude to climate change. As a result, all nations agree that ecosystem restoration is urgently required on a vast scale. This call to action was most recently formalised in the Kunming-Montreal Global Biodiversity Framework, in December 2022, an agreement which commits 196 countries to halting and reversing nature loss by 2030.

The framework is comprised of 23 targets, including a global target to conserve at least 30% of the world's land, freshwater and seas for nature by 2030. At a national level, the UK has formally committed to protect and conserve a minimum of 30% of land and sea for biodiversity by 2030, a target known as 30 x 30[5]. With an increasing amount of UK nature restoration projects taking a process-led approach, it is likely that rewilding will contribute significantly to achieving these statutory targets for nature recovery.

This backdrop of an increasing ambition for rewilding projects in Britain adds further impetus to the need to improve understanding of such projects' carbon sequestration and storage potential. This information will allow rewilding projects' effectiveness as a climate solution to be quantified and, as explored further in Section 5, may enable their financing through ecosystem markets such as the UK VCM.

Section 2: Rewilding

2.6 Rewilding in practice: Knepp Estate, West Sussex

This project's data collection was focussed on Knepp Estate, a well-known process-led nature restoration project in southern England. As a rewilding case study, Knepp is instructive in terms of the approach taken and the resulting habitats that have emerged.

2.6.1 Knepp Estate – A rewilding case study

The main area of rewilding at Knepp Estate is known as the 'Southern Block' and comprises approximately 430 hectares of low weald clay land previously ploughed and then farmed conventionally for arable and dairy until around 2002. At that point in time, approximately 356 hectares of the Southern Block was arable, 41 hectares was in pasture and the rest was made up of blocks of woodland and hedgerows.

From 2003 – 2006, the area in arable farming (cross hatched in Figure 7) was reduced each year, and eventually stopped entirely in 2006, coming out of production on a field-by-field basis. Around 20ha was taken out of production before and during 2002, 87ha was left fallow in 2003, 50ha in 2004, 163ha in 2005 and the remaining 30ha in 2006. At the end of each harvest, the fields on this very heavy clay land were left as stubble and allowed to rest. They were naturally colonised by grasses, shrubs and trees with no human inputs or interventions and only a few roe deer and rabbits representing the grazing pressure until 2009.

By allowing the fields to begin recovery after the cessation of ploughing, chemical application and arable farming, the soils began to repair themselves and the seeds from the woodlands, grass margins and hedgerows began to colonise the ex-arable fields, facilitated by tree planters such as jays and field mice.

In 2009, a deer fence was erected around the Southern Block and a range of free roaming herbivores were introduced, including Fallow Deer, Old English Longhorn Cattle, Exmoor Ponies, Tamworth Pigs and a few years later Red Deer.

These animals shaped the ecosystem, each foraging (grazing and browsing) in different ways. They influenced the vegetation as it grew, creating a mosaic of habitats that were then occupied in turn by countless other taxa. What has followed is significant biodiversity recovery, with Knepp transforming from an ecologically degraded farm to a thriving ecosystem.

As a case study, Knepp's southern block is instructive, indicating the biodiversity uplift that can be delivered by process-led nature restoration projects. Within twenty years, Knepp has created one of the highest densities of breeding songbirds in the country. These biodiversity gains have been achieved whilst simultaneously more than trebling rural employment at Knepp Estate from 23 to 80 FTEs.

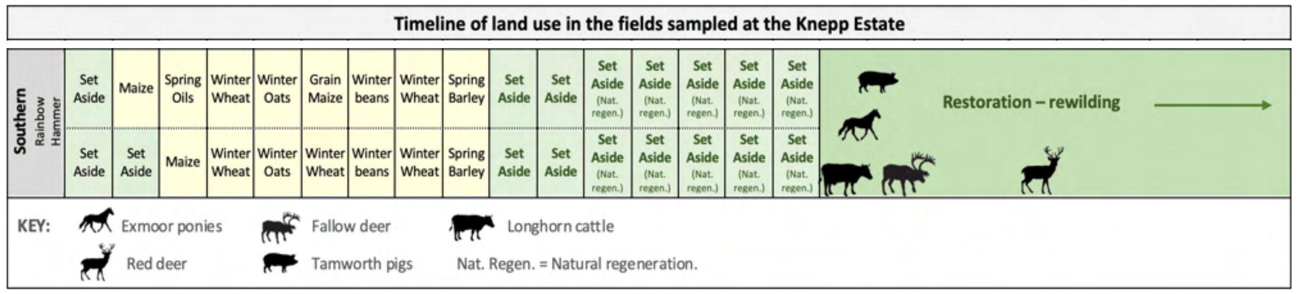


Figure 5
Land use on two typical fields in the Southern Block at Knepp Estate from 1993 - 2019[6]
Credit: Sarah Davidson, Cranfield University

Note that the location of animal symbols on the timeline indicate the time of their introduction.

Image 2
Old English Longhorn Cattle browsing and grazing scrub, trees and grassland at Knepp. Photo Credit: Knepp Estate

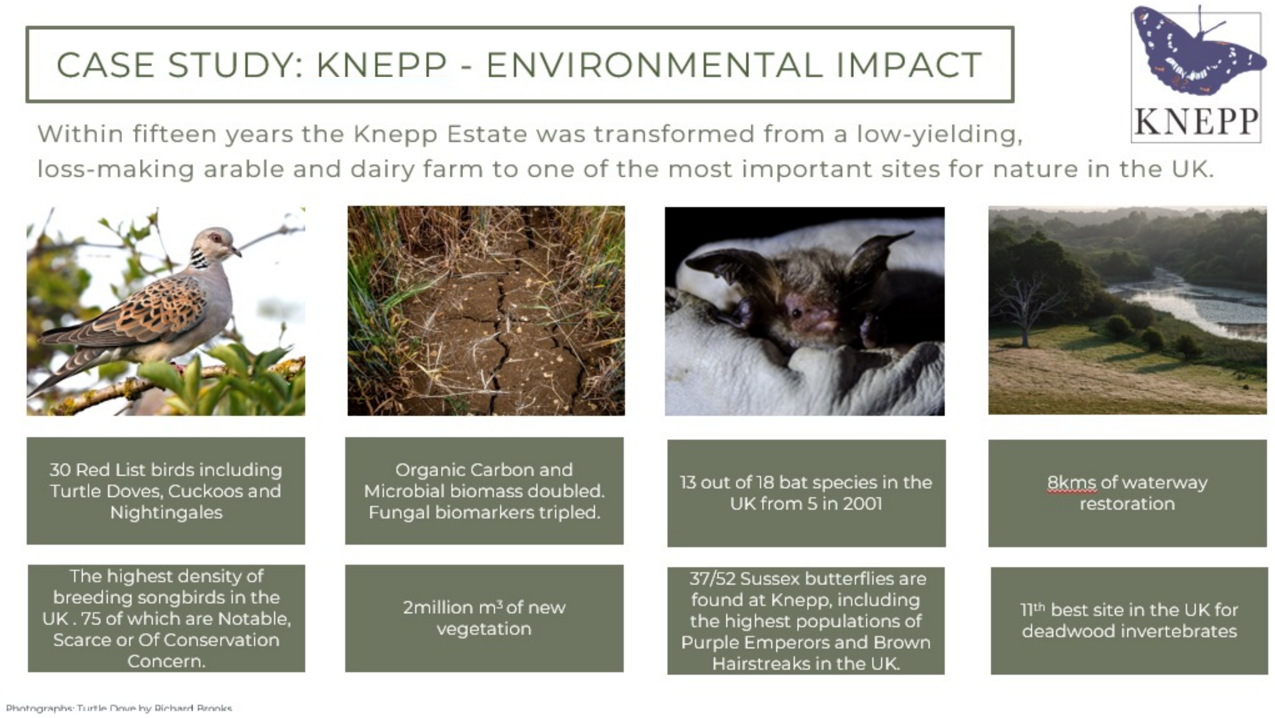


Figure 6
Knepp Environmental Gains

Section 2: Rewilding

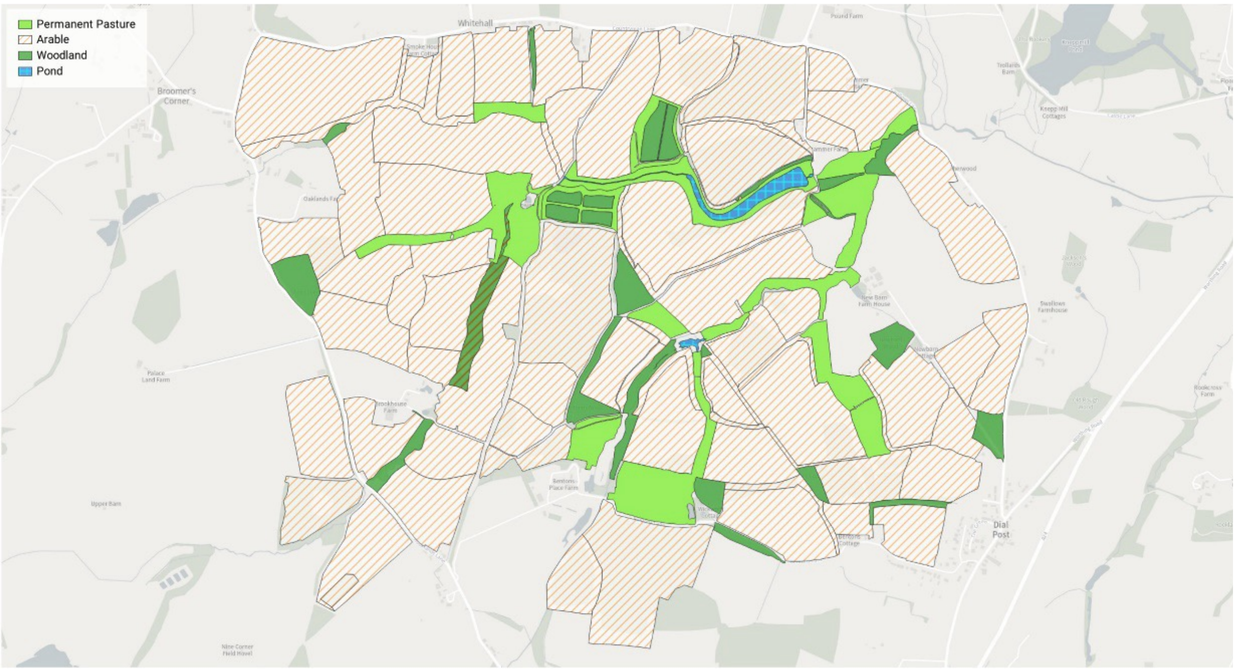


Figure 7
Knepp as an arable farm in 2003

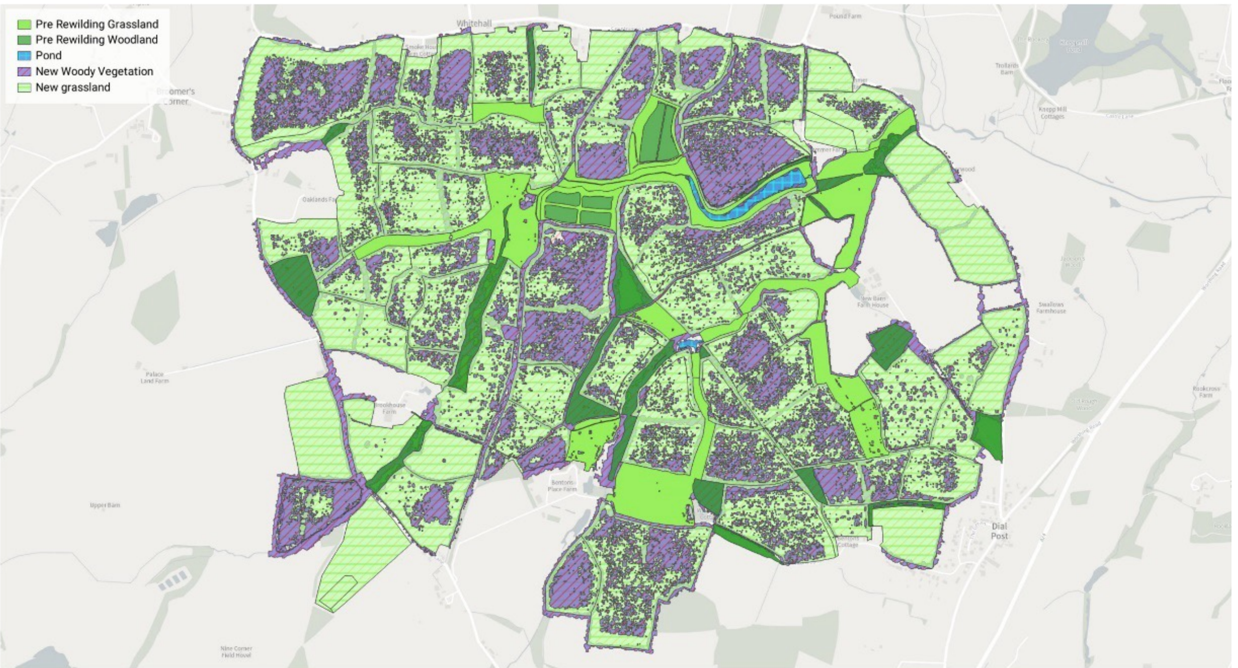


Figure 8
Knepp Southern Block habitat types, 2019. In purple is all new woody vegetation including scrub, young woodland and expanded hedgerows

03

Evidence & data gaps

Section 3: Evidence and Data Gaps

Key driver for this project

To understand the current evidence base for the carbon sequestration and storage potential of ‘rewilding habitats’, this project reviewed existing literature and identified key data gaps that still exist around the relationships linking woody biomass and carbon in scrub species.

3.1 Context

As mentioned in Section 1.2, there is a need to better understand the carbon sequestration and storage potential of process-led nature restoration projects. This will allow the climate impact of such projects to be quantified and could also provide such projects with access to new sources of funding, through ecosystem markets like the UK VCM.

At the current time, the VCM is dominated by certified carbon credits generated from discrete habitat types, such as woodlands or peatlands. In the UK, government-backed carbon standards exist for both of these habitat types and allow high-integrity carbon credits to be generated and sold[7 8]. However, as described in Sections 1 and 2, process-led biodiversity restoration often leads to dynamic habitat mosaics, where multiple habitat types including grassland, scrub, wood pasture and woodland, are intimately mixed across landscapes.

This presents a challenge for both the measurement and estimation of carbon sequestration, as there are an increased number of variables compared with single-habitat types. Rather than being comprised of ‘woodland’, ‘wetland’ or ‘grassland’, ‘rewilding habitats’ can and often do include elements of all three, and other habitats, with the ratio of each constantly changing over time.

Nonetheless, process-led nature restoration has been shown to improve ecosystem integrity and function, in part due to the dynamism and complexity that makes measurement difficult. As such, it should be supported and incentivised as a nature-based solution (NbS) that can help society combat both climate change and the loss of biodiversity. To do this will require robust methodologies for measuring and estimating the carbon sequestration and storage potential of ‘rewilding habitats’, so that practitioners and project developers have greater certainty about the carbon impact of their projects.

With this objective in mind, the Knepp Wildland Carbon Project set out to understand what evidence base exists for carbon sequestration in ‘rewilding habitats’ and identify the data gaps that remain.

3.2 Current evidence base

3.2.1 Overview

The project reviewed the existing evidence base for the habitats that emerge in terrestrial rewilding projects in lowland Britain, with an assumption that these would be taking place across primarily inorganic soil types.

A key resource for the project team was the Natural England Carbon Storage and Sequestration by Habitat paper (**NERR094**)[9], which is referred to throughout this report. In conjunction with other literature, the following section summarises the limited evidence base around carbon storage and sequestration across different habitat types that would be expected to emerge in a process-led nature restoration project.

3.2.2 Grasslands

According to the NERR094 review,

> “ *Open habitats such as heathlands and semi-natural grasslands sequester and store more carbon than modern agricultural landscapes but typically store less carbon than peatlands, saltmarsh and established woodlands* ”.

The NERR094 review largely focuses on the stock of carbon in different types of historic or established grassland, rather than looking at how carbon sequestration develops as the habitat moves from arable or ‘modified’ grassland into a restored grassland. However, it does reference a study by Warner et al. (2020) that takes a lifecycle assessment approach, and reports the soils in a “reversion of arable land to low input grassland under Countryside Stewardship will sequester **1.590 tCO_2e ha-1 y-1**” over a 10-year period.[10] In a separate paper by Smith et al (2010), the sequestration rates in the soils of an arable reversion to grassland project resulted in a mean sequestration rate of 3.04 tCO_2e ha-1 y-1.[11]

From this limited pool of studies, a range of **1.17 – 4.91 tCO_2e ha-1 y-1** has been identified for soil carbon sequestration in arable reversion to grassland projects, with a mean estimate sequestration rate of **3.04 tCO_2e ha-1 y-1**.[9]

This is a wide range and highlights the uncertainty that still exists as a result of a narrow evidence base. In addition, both of the studies referenced above were carried out over relatively short time periods, assuming a saturation rate of 20 years. What is not known is what happens for the next 20 years or 40 years and how the addition of new scrub, woodland and natural processes on the grassland impacts the soil carbon stock.

Section 3:
Evidence and Data Gaps

3.2.3 Scrubland

The NERR094 review defines scrubland as,

"*all stages from scattered bushes to closed canopy vegetation, dominated by locally native or non-native shrubs and tree saplings, usually less than 5m tall, occasionally with a few scattered trees*".

Image 3
20 years of natural colonisation of scrub and unmanaged growing hedgerows at the Knepp Estate.
Photo Credit: Knepp Estate

Carbon sequestration rates in scrub are one of the major data gaps within terrestrial habitats in the UK, with studies on scrub carbon mainly coming from Mediterranean or boreal regions in Europe. [9]

Nevertheless, some UK-based projects do provide insight on scrubland carbon such as the Rothamstead Wilderness Experiment[12], in which an arable system was reverted to woodland through natural colonisation with no livestock over a 122-year period. An oak-dominated, calcareous section of the site sequestered 2tCO_2e ha-1 y-1 in the soil beneath the regenerating trees and 10.5 tCO_2e ha-1 y-1 in the woody biomass of the trees and roots, whereas an acidic section of the site sequestered 1.4 tCO_2e ha-1 y-1 and 5.9 tCO_2e ha-1 y-1 respectively.[12]

It is important to acknowledge the limitations of this comparison, given the length of the study and with both sites now being mature woodland rather than scrub. In addition, unlike 'rewilding habitats', the habitats in this experiment did not have the interactions with large herbivores, such as dunging, trampling, and poaching the soils. These herbivore-driven processes have been shown to rejuvenate the soil ecosystem, restoring worm populations and speeding up the rate of soil carbon sequestration.[13]

Within the NERR094 review, the evidence demonstrates that within scrubland habitats the majority of carbon sequestration for the first 20 - 30 years occurs below ground, within the soil. After this timeframe, the sequestration becomes increasingly focussed above ground, in the woody biomass of scrub and trees.[14]

This is consistent with the data uncovered by this project on Knepp Estate and strengthens the NERR094 review's conclusion that carbon sequestration in the first 20 – 30 years of a rewilding project is primarily driven by soil recovery, which results from the ecological processes of natural colonisation, grazing, trampling and dunging. After this time, the accumulation of carbon in the woody biomass of well-established trees and scrub begins to dominate as the soil trends towards carbon saturation.

Despite this, significant data gaps remain, in particular around (a) the allometric equations that describe the relationships between individual woody species and carbon, and (b) the root-to-shoot ratios for typical UK scrubland species (such as blackthorn, willow spp., hawthorn and dog rose), especially when exposed to grazing and browsing. While some proxies exist from studies on hedgerows and productive forests, these are not analogous to non-linear scrub habitats. This fact has been highlighted by recent research from the University of Oxford, which determined that scrub on Knepp Estate had a root:shoot ratio of 1.07, more than four times the amount predicted by widely-used estimates, such as the i-Tree Eco model's ratio (0.26).[15]

3.2.4 Hedgerows

As mentioned in Section 3.2.3, new hedgerows, or the expansion of existing hedgerows, may be the best proxy for natural colonisation of scrub on previously farmed land. However, direct comparison is difficult due to the linear nature of hedgerows, with many relevant studies referring to hedgerows only as a length, instead of an area. In addition, as with the Rothamstead Wilderness Experiment referenced above[12], these studies also do not account for interactions between hedgerows and free-roaming herbivores.

Nevertheless, the data still supports significant carbon sequestration potential for hedgerows and their associated soils, with Falloon et al. (2004) estimating rates of **3.67 tCO_2e ha-1 y-1**[16]. Additionally, regrowth of larger trees within hedgerows can further increase carbon sequestration in these habitats, possibly by up to **1.6 tCO_2e ha-1 y-1** for 2 trees per 100m of hedgerow.[17]

3.2.5 Woodland

In comparison to the other habitat types covered in this section, woodlands have been very well-studied. This is due to their economic importance for timber production and, increasingly, carbon sequestration and storage. Many studies have focussed on above-ground biomass, although the evidence base for woodland soils is now increasing.

Most allometric equations between carbon and tree size (for woodland habitats) have been derived from tree species that were (or are) grown productively, for timber. They are based on calculations involving the diameter at breast height (DBH) and governed by the assumption that trees are planted close together and in compartments. It is these equations that underpin the look-up tables on which the Woodland Carbon Code's (WCC) carbon calculator is based. This project has used data from the WCC carbon calculator to explore above and below-ground sequestration rates for new woodlands and compare these with other habitat types.

Based on the WCC calculator, a typical mixed native woodland planted on previously arable land in lowland Britain will sequester **6.63 tCO_2e ha-1 y-1** above ground over 100 years and a further **0.46 tCO_2e ha-1 y-1** into the soils.[1] However, initial total sequestration rates are lower, with an average of **5.50 tCO_2e ha-1 y-1** achieved above ground and **0.55 tCO_2e ha-1 y-1** into the soils during the first 20 years after planting.[1]

The Rothamstead study offers insight into the comparative rates for a woodland established through natural colonisation, which is more analogous to the habitats that emerge on rewilding projects[12]. Over 122 years, this study concluded that naturally regenerated woodland sequestered between 7.34 and **12.44 tCO_2e ha-1 y-1**, the large range being reflective of the variable soil types and the higher complexity of estimating carbon sequestration of a rewilding project over a planted system.

Section 3:
Evidence and Data Gaps

3.3 Summary and discussion

The data on sequestration rates discussed in the sections above is summarised in Table 1 (below). Of note, is the fact that the project team did not attribute ‘high’ confidence to any of the rates identified. The project also highlighted that crucial data gaps exist around scrub species, in particular a lack of knowledge of the allometric equations and root-to-shoot ratios that would elucidate the relationships between woody biomass and carbon sequestration and storage for these species. Table 1 summarises the carbon sequestration of land use change by habitat type.

Given the central importance of scrub habitats in process-led nature restoration projects, it is essential that these relationships are understood so that future carbon estimates are not based on extrapolating from data on hedgerows. Fortunately, the University of Oxford is leading a 4-year study that started in 2021 at the Knepp Estate examining this exact question. If successful the research will plug multiple remaining data gaps; including identifying allometric equations for carbon in multiple scrubland species and their root:shoot ratios under a variety of browsing pressures.

This study is destructive sampling 290 trees from Knepp and measuring how much carbon is within each of these trees and their roots. Providing allometric equations and root:shoot ratios for all the dominant scrub and tree species at Knepp. The sampling is split into ‘exposed’ to browsing herbivores and ‘protected’ from browsing herbivores and will cover Blackthorn, Dog Rose, Hawthorn, Oak and Sallow.

Another data gap this project identified is the lack of studies for different habitat types that run for a comparable duration. Without this, it is difficult to understand the time to carbon saturation that exists for different habitats within a rewilding project. The Woodland Carbon Code, for example, models new woodlands as reaching carbon saturation after 100 years, after which point their stock of carbon is considered to be stable, with emissions from decay balancing out ongoing sequestration of atmospheric CO_2. For soils, the timeframe is less certain with estimates ranging from 25 – 150 years, depending in part on the soil organic matter (SOM) content that is present initially.[9]

Finally, the project team noted that within the existing literature most research focuses on individual habitat types rather than composite habitats or dynamic mosaics. Likewise, most attention was paid to habitats at a given point in succession, rather than exploring how succession itself influences carbon sequestration and storage within these habitats over time. Long-term, comparative studies of process-led nature restoration projects should help to plug these data gaps.

Habitat	Below-ground sequestration (tCO_2e ha-1 y-1)	Above-ground sequestration (tCO_2e ha-1 y-1)	Midpoint of total rate of sequestration (tCO_2e ha-1 y-1)	Confidence	Time Period
New hedgerows	Unknown	1.99- 5.27	3.63	Low	Unknown
Arable reversion to grassland	1.17 – 4.91	0	3	Medium	20 years
Arable reversion to woodland (tree planting) [13]	0.55	5.50	6.05	Medium	20 years
	0.46	6.63	7.09	Medium	100 years
Arable reversion to woodland (natural colonisation) [9]	1.4 - 2	5.9 - 10.5	10	Medium	50 - 120 years

Table 1
Carbon sequestration of land use change

3.4 Recommendations

This project has highlighted the complexity involved in estimating carbon sequestration and storage in ‘rewilding habitats’, in part due to the data gaps discussed in Section 3.3.

It is clear, therefore, that continued research, combined with rigorous monitoring of existing process-led nature restoration projects, will be essential. Over time, this will reduce the uncertainty involved in estimating the carbon impact of ‘rewilding habitats’. Nonetheless, even based on the existing literature, it is clear that ‘rewilding habitats’ do sequester and store carbon. Practitioners can therefore be confident that process-led nature restoration is having a positive climate impact. The challenge is to refine carbon estimates, so that sequestration and storage can be forecast more accurately and therefore provide a stronger basis for investment.

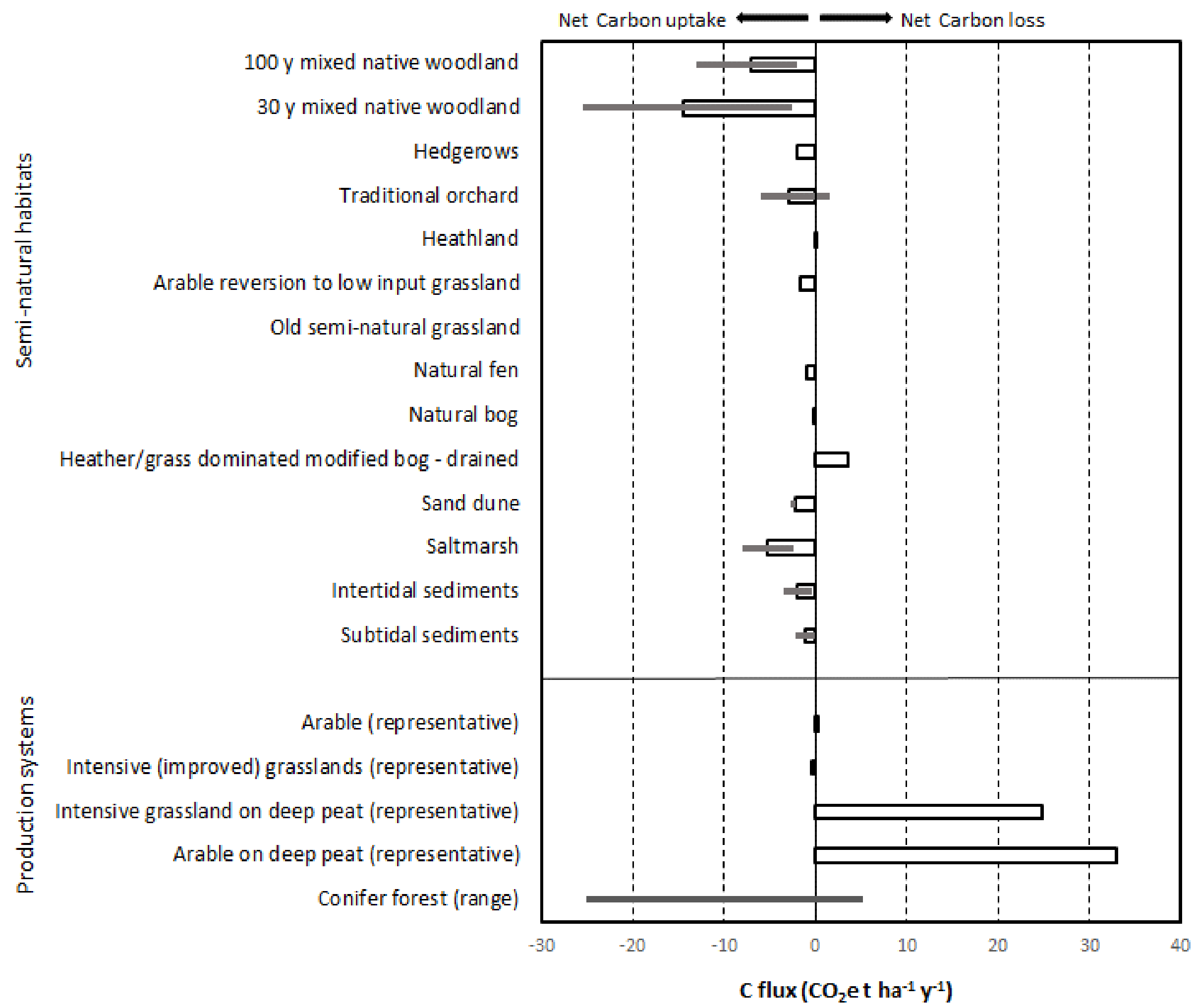


Figure 9
Carbon flux in contrasting habitats and land managements (Natural England Research Report NERR094. Natural England, York.RR094).[9]

Best available data have been used and includes data from a wide range of different sources, modelled and field data. A negative value indicates sequestration, positive values are emissions. The grey bars indicate the likely range of values across sites where this is available. Habitats with no suitable data are not included.

04

Carbon sequestration on Knepp Estate

Section 4: Carbon sequestration on Knepp Estate

4.1 Overview and timeline

A key objective for the Knepp Wildland Carbon Project was to undertake primary data collection from Knepp Estate, to determine the carbon sequestration and storage that has occurred since the inception of process-led nature restoration in 2003.

The act of data collection also allowed the project team to compare different approaches to baselining and monitoring, reporting and verification (MRV) for rewilding projects. Specifically, this involved the use and comparison of different technologies, which were deployed to compile a robust and complementary data set that captured the above and below ground changes in carbon sequestration and storage that have occurred at Knepp. Learnings from this process are outlined below and have fed into the project's recommendations in Section 6.

Figure 10 outlines the project timeline, showing when the each stage of data collection and analysis occurred. Table 2 describes the project partners and Section 4.2 describes, in more detail, the different approaches that were trialled.

Organisation	Organisation overview and project role
KNEPP	The Knepp Estate: A privately-owned estate with one of the best known process-led nature restoration ('rewilding') projects in the UK, which started over 20 years ago in 2003. The 1,400-hectare Knepp Estate in West Sussex provided the data required for this project to generate scrub and soil carbon models for 'rewilding habitats'.
NATTERGAL	Nattergal Ltd: A commercial enterprise delivering nature recovery at scale to provide vital benefits for society and sustainable financial returns. Nattergal aim to help deliver global biodiversity recovery, driven by focused investment into rewilding degraded ecosystems. Nattergal's first and flagship site, Boothby Wildland, located in Grantham, Lincolnshire, is a 617 hectare grade 3 arable farm, which will follow the 'Knepp Model' of process-led nature restoration.
Queen Mary University of London	Queen Mary University of London: QMUL worked with the project team to upscale and evaluate the utility of low-cost remote sensing approaches for monitoring process-led nature restoration projects.
Treeconomy	Treeconomy: A company who use technology to quantify and track projects, providing quality data to underpin emerging marketplaces. Treeconomy have been undertaking drone flights over the Knepp and Boothby test sites, collecting data to model above- and below-ground woody biomass and calculating carbon stocks.
Agricarbon	Agricarbon: A company working to provide affordable, accurate soil carbon stock audits, based on high-intensity direct sampling, that underpins carbon-buyer confidence in soil carbon sequestration. Agricarbon are undertaking sampling of over 1,000 cores across Knepp Estate and adjoining arable farms, to analyse the soil carbon sequestration on the site.
ARUP	Arup: Dedicated to sustainable development, Arup is a collective of designers, consultants and experts that has been providing project management and stakeholder engagement support, alongside environmental economics expertise and research on routes to market for nature restoration projects.

Table 2
Project Partners

Case study site:

Knepp Estate, West Sussex

Knepp Estate is one of the most prominent examples of rewilding in the UK. Established for over 20 years, Knepp has an international reputation for pioneering rewilding and large-scale habitat restoration. The 1,400-hectare site, previously used for intensive farming, was restored to a process-led and wild state. Today, Knepp is home to a mosaic of diverse habitats and ecosystems, including woodlands, wetlands, scrubland, and grasslands. Knepp finances rewilding through ecotourism, accommodation, events and workshops, partnerships, grants, philanthropy, education and outreach.

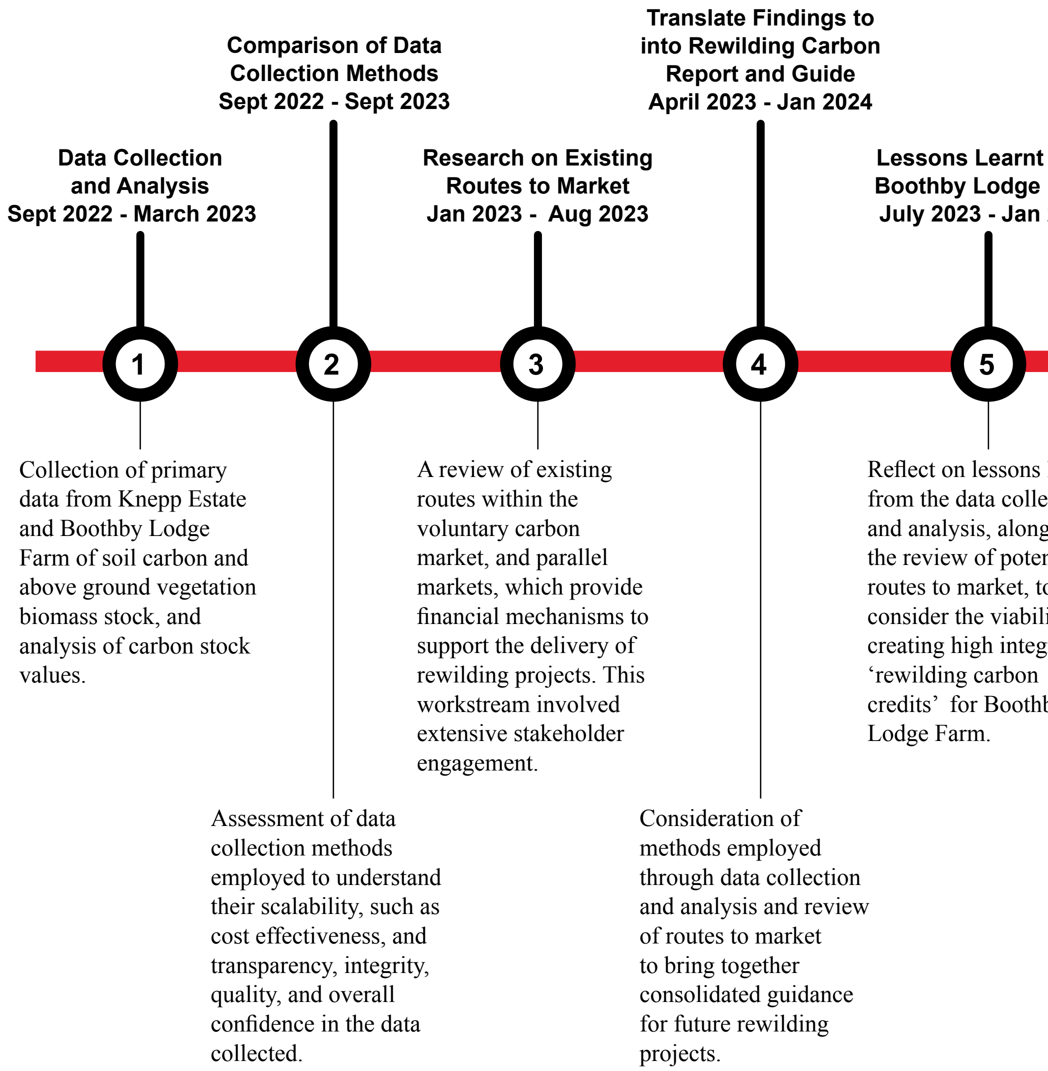


Figure 10
A schematic showing the chronology of the Knepp Wildland Carbon Project

Section 4:
Carbon sequestration on Knepp Estate

4.2 Data collection: Approaches and technology

This project aimed to both determine the carbon sequestration rates at Knepp over the past 20 years and to find the best methods for baselining and tracking change in carbon stocks across rewilding projects. With a huge range of 'nature tech' monitoring options being marketed to landowners, the project aimed to understand which methodologies had the highest integrity whilst also being cost efficient.

The monitoring methods tested also informed the sequestration rates at Knepp and have shaped the scientific data that has emerged from this project. It is important to note that to inform the scientific studies, an extremely comprehensive sampling rate was required to build data confidence. However, having achieved this, future projects would not require such high levels of investment and sampling.

There were three digital technologies reviewed as part of this analysis, selected based on their ability to collect data across large, heterogeneous restoration projects, and their potential for scalability:

Method 1
Drone and LiDAR surveying, for remote sensing-based analysis of tree and scrub above and below-ground biomass (undertaken by Treeconomy).

Method 2
Drone and Structure-from-Motion photogrammetry, to produce canopy surface models (undertaken by Queen Mary University of London).

Method 3
Below ground carbon analysis, through a soil carbon audit of Knepp Estate and an arable control site (undertaken by Agricarbon).

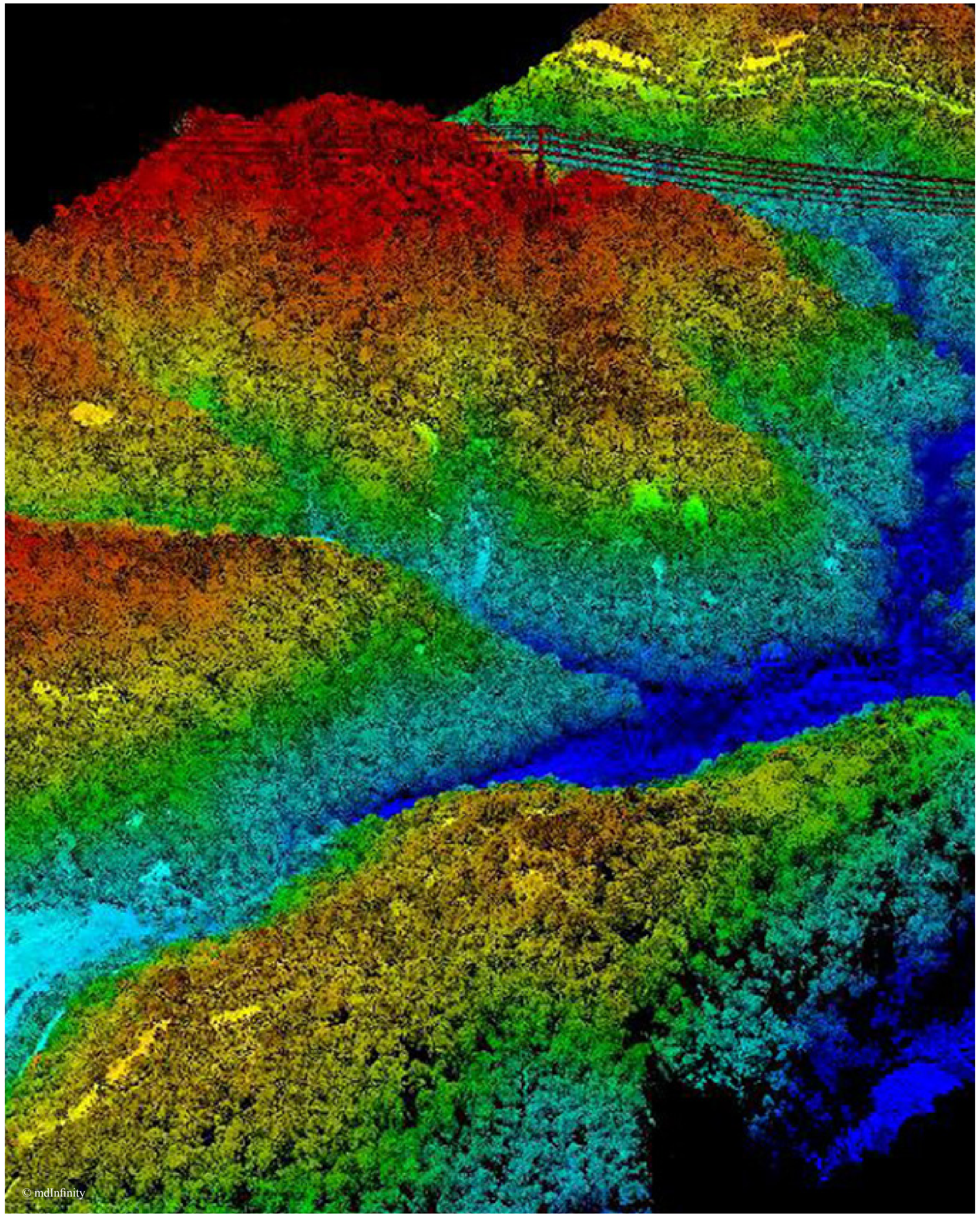
Each of these methods, and the technologies underpinning their approach, were analysed for their cost effectiveness, replicability and data integrity. It should be noted that none of the methods requires the use of a specific provider or contractor. These were the partners selected for the Knepp Wildland Carbon Project, bringing together an innovative collaboration between a private landowner, natural capital company, engineering and sustainability consultancy, academia and technology-based carbon measurement companies.

To calculate volumes of woody biomass that have been created through process-led nature restoration at Knepp, Treeconomy and QMUL were able to look at historic baselines using satellite and Environment Agency LiDAR data from 2001, to compare against the present day. Agricarbon were able to use a series of fields in an adjacent arable farm, which had the same soil types and hydrology as Knepp's 'Southern Block'.

The tables below provide a more detailed comparative analysis of the three methods that were trialled.

Section 4:
Carbon sequestration on Knepp Estate

4.2.1 Method 1:
Drone and LiDAR remote sensing-based data collection



Overview	Remote sensing- based survey using drones to collect LiDAR point cloud data to estimate above and below ground scrub and tree biomass
Survey Method	Treeconomy measured the baseline biomass of two vegetation components at Knepp: 1) scrub habitats and 2) trees/woodland. Additionally, the uplift of scrub biomass between the years 2001 and 2022 was measured (the increase in extent, height, volume, and biomass during a given time range).
Baseline Data Used	1) LiDAR: Digital Terrain Model (DTM, 25 cm); Digital Surface Model (DSM, 25 cm) 2) Queen Mary University of London extent, height, and volume derived datasets (based on the free National LiDAR data programme, England)
Technology Used	Drones and LiDAR (Light and Detection Ranging)
Survey Deployment	A drone carrying a LiDAR sensor/receiver was programmed to survey the extent of Knepp Estate, resulting in the collection of a dense point cloud, geographically-referenced photo of the site, a DTM, and DSM. These data were used to build a Canopy Height Model (CHM), which shows the height of the vegetation above the ground level. This data was used to estimate the extent and volume of different habitats (scrub, woodland), and used as input to feed models which predict the biomass of these specific habitats.
Practical Barriers	This method is best deployed between late spring and early autumn, when foliage of the habitats are fully out. This is because the height profiles of scrub and shrub can be more accurately ascertained from the LiDAR sensor. Additionally, the likelihood of rain, sleet, and poor lighting conditions are reduced during these seasons, which interfere with the drone's ability to image the environment effectively.
Skill Level	This method requires either expertise in the deployment of drones and their survey equipment (or the finances to contract for this service), and in data analysis of the acquired imagery. In some cases, the LiDAR data may be freely available through government agencies, but knowledge of how to handle the datasets is still required from persons with a background in remote sensing and geomatics.
Cost	The cost of operating a survey can range from free (if the data already exists), to several thousands of pounds, depending on the size of the project site. The data analyses can have a similar cost range, depending on the availability of the required expertise. Drone data can be £12 - £30/ha.
Scale	The method is effective for project sites of up to several hundred hectares with potential for larger areas as the capability of technologies increase.
Timescales	Data capture can take 1 to several days for the drone survey itself, with varying time to process the collected data to be ready for analysis. Analyses vary in time depending on the quality of the data and the total area needed to be analysed, with more complex environments requiring additional time. For a project of up to several hundred hectares, this method could be completed in a few weeks.
Outputs	The products generated from this method are: 1) A 3D point cloud of the survey area; 2) GIS raster layer of the canopy height model (CHM); 3) GIS raster layer of height, volume increase; 4) GIS vector layer of scrub extent; 5) PDF maps of the layers in relation to the project site; 6) Tabular data summarising area, volume, and biomass of the vegetation.

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Carbon sequestration on Knepp Estate

4.2.1 Method 2:
Drone and Structure-from-Motion photogrammetry software

(a) DJI Air 2S (left) and (b) DJI Mini 2 (right) UAVs

Overview	Using low-cost Unpiloted Aerial Vehicles (UAVs) and applying Structure-from-Motion photogrammetry software to quantify the 3D structure of complex vegetation assemblages.
Survey Method	Drone flights to capture aerial imagery, in leaf on and leaf off conditions to facilitate photogrammetric 3D reconstruction of rewilded vegetation structure. GNSS-surveyed ground control points used to accurately position and scale models. Digital Surface Models (DSMs) of the study area were reconstructed using Agisoft Metashape Structure-from-Motion (SfM) photogrammetry software. In addition, the leaf-off and leaf-on UAV LiDAR datasets were collected for validation and classified to develop ground models and vegetation point clouds.
Baseline Data Used	n/a
Technology Used	– Riegl Ricopter UAV equipped with miniVUX-2UAV laser scanner, Applanix APX-20 IMU/GNSS system, Sony Alpha 6000 RGB camera (24.3 MP), Sony Alpha 7R III multispectral camera (8 MP per spectra channel) and Teledyne FLIR Tau 2 thermal camera, – DJI Air 2S UAV equipped with 20 MP RGB camera, – DJI Mini 2 UAV equipped with 12 MP RGB camera.
Survey Deployment	Field surveys were undertaken in the Knepp Estate's Southern Block during leaf-off (17 March 2023) and leaf-on (15 August 2023) conditions. A network of 20 black and white ground targets with dimensions of 1m x 1m to support photogrammetric reconstruction were deployed within a study area containing rewilded hedgerows, bramble, thorny and sallow scrub, isolated mature oaks and ancient woodland approximately 500m southwest of New Barn Farm.
Practical Barriers	The ability of this approach to produce accurate canopy surface models of rewilded vegetation and the sensitivity of these models to methodological aspects including ground control, photo angle and survey conditions (leaf-off vs leaf-on) are detailed in Appendix 2 & 3.
Skill Level	This method requires expertise in the deployment of drones and their survey equipment (or the finances to contract for this service), and in data analysis of the acquired imagery.
Cost	High cost option
Scale	The method is effective for project sites of up to several hundred hectares with potential for larger areas as the capability of technologies increase.
Timescales	Data capture can take 1 to several days for preparing survey plan and the drone survey, with varying time to process the collected data to be ready for analysis.
Outputs	1) SfM photogrammetric reconstructions 2) LiDAR data 3) Canopy Height Model (CHM) development and vegetation volume estimation.

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Carbon sequestration on Knepp Estate

4.2.2 Method 3: Soil carbon stock audit

Agricarbon soil core sample

Overview	Below ground carbon analysis – soil carbon stock audit of Knepp Estate
Survey Method	Stratified random sampling within project areas with soil coring to depth (up to 100 cm) that can be divided into representative soil depth layers (e.g., 0-15, 15-30, 30-60, 60+cm) for laboratory analysis
Baseline Data Used	1) Land use and management information from the clients 2) Digital maps of the project area and associated fields, farms etc, where available from project team otherwise prepared by Agricarbon GIS team. 3) Available digital and other data sources to design stratified random sampling e.g. soil types, parent material, terrain. 4) Existing soil carbon stock data from this location or equivalent areas from project or literature or Agricarbon's data resource to help guide sampling intensity with an assessment of Minimum Detectable Difference (MDD).
Technology Used	Soil core extraction vehicles with hydraulic extractors; industrial-scale innovative laboratory analysis of soil organic carbon (g kg-1) and fine dry bulk density (g cm-3); extensive data resource on soil carbons stock to depth
Survey Deployment	Coring locations selected by random allocation within strata e.g. 15 cores per field area but core N will depend on project requirements e.g. MDD. Core locations downloaded to field team (App and GPS) who then follow detailed protocol to locate and core. Intact cores returned to Agricarbon laboratory for soil organic carbon and bulk density analyses. The laboratory component is a unique process that measures both SOC% and bulk density for every sample.
Practical Barriers	– Access is often dictated by land management timings e.g. post-harvest / pre-planting for arable crops, silage cutting in grasslands. – General weather conditions in the growing season do not limit access (e.g. wind and rain) however, there are health and safety limits to working under extreme weather conditions (e.g. lightening, high winds, flooding, etc) – Soil sampling cannot be carried out where ground is waterlogged or frozen or after recent management that would adversely influence soil carbon stock measurement (e.g. Farmyard manure (FYM), liming).
Skill Level	– Business Team - inter-personal communications, familiarity with soils, land use and management systems, and carbon markets (e.g. VCM, Scope 3, etc), spreadsheets, budgeting. – Sampling Design – GIS, spatial data analysis, mathematical and statistical analysis, familiarity with soils, land use and management systems. – Field Team – off-road / 4x4 driving, towing, coring, logistics, inter-personal communications, mechanical. – Laboratory Analysis – soil processing, GC analysers, engineering, mathematics, software programming. – Quality Management and Reporting – QC/QM, mathematics, statistics, data systems, programming, spreadsheets.
Cost	An approximate cost would be less than £20 per core which includes 4 samples to depth. However, there is no universal cost per hectare since scale, extent and requirements of projects influence the final cost per core.
Scale	Can be deployed at any scale and will impact on cost e.g. larger site means economies of scale and lower average costs.
Timescales	Most time is required at the start of the project, working with the client to devise a suitable sampling strategy. This can take a few hours to a number of days depending on how complex the project is. Once the project requirements have been confirmed then it can be a matter of a few days before sampling can commence. Field sampling can be rapid with c. 100 cores feasible per day, depending upon local conditions and travel between sampling locations. Laboratory analysis is high throughput and soil samples are generally analysed and reported within a few weeks of field sampling.
Outputs	Reporting includes: soil carbons stock (t/ha), soil carbon content (%), total soil bulk density (often used for compaction assessments) and fine dry bulk density (required for soil carbon stock calculations). Statistics can be prepared by sample, core, field, farm, project, etc.

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Carbon sequestration on Knepp Estate

4.3 Results and analysis

Each of the project partners produced their own reports, summarising their approach and the results of their analysis, which can be found in the Appendices. This section summarises the main findings of each partner and discusses the implications of their results.

It is important to note that each analysis took 2003 as its baseline year because this is when arable reversion began in parts of the Southern Block at Knepp Estate. However, as shown in Section 2, most arable land was not taken out of production until 2005, implying that the sequestration rates recorded below are conservative and likely to be under-estimating the true annual rate.

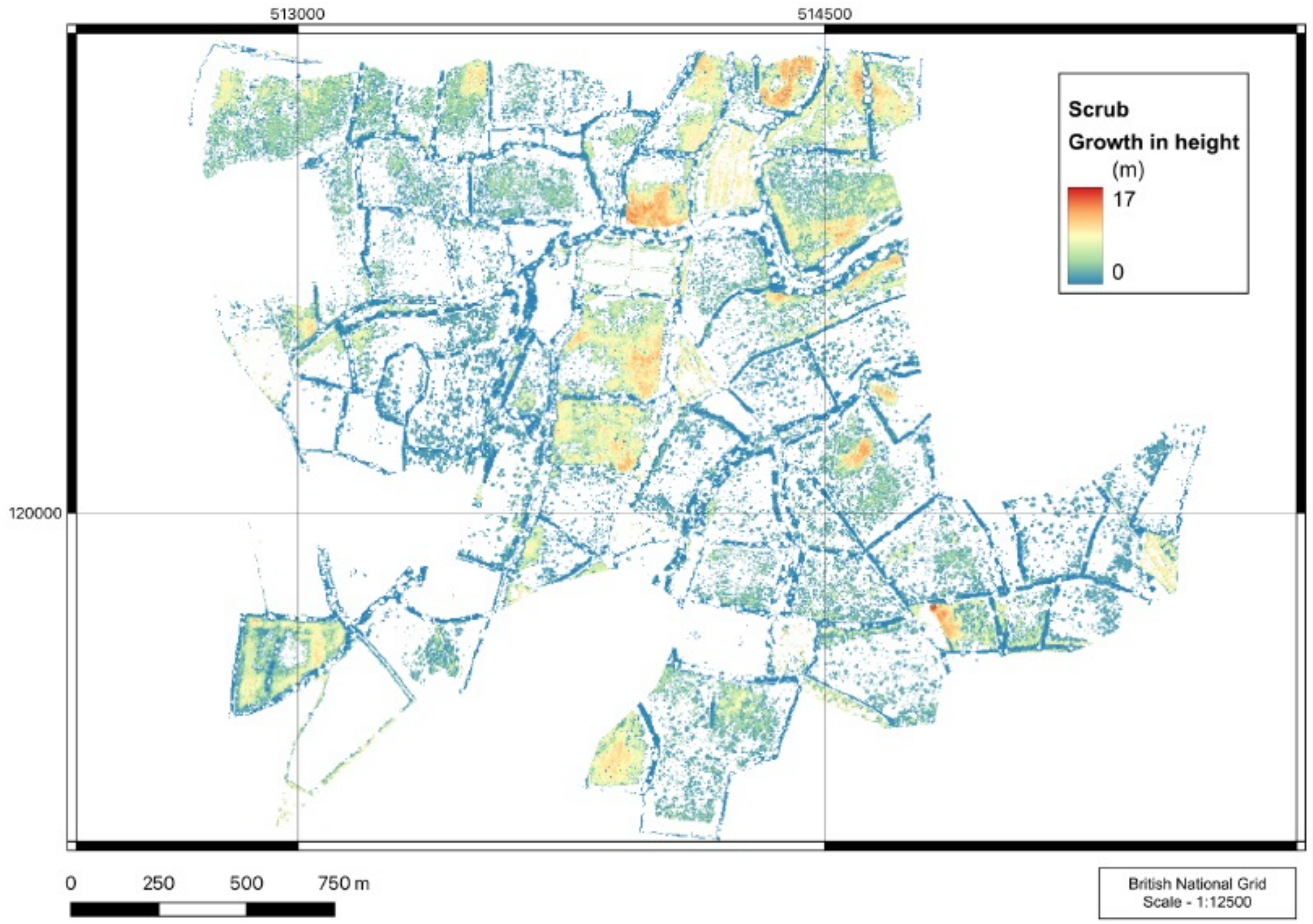

Figure 11
Treeconomy scrub regeneration model

4.3.1 Method 1 – LiDAR + Photogrammetric analysis with Axe et al (2017) allometric equations undertaken by Treeconomy (Appendix 1)

Using drones to photogrammetrically and LiDAR survey Knepp's Southern Block in 2022 allowed Treeconomy to build up a three-dimensional model of the landscape, as shown in Figure 14. In the absence of allometric equations for open grown scrub (a data gap being filled by the University of Oxford), Treeconomy made volumetric estimates from their 3D model and then applied hedgerow allometric equations as outlined in a study by Axe et al. (2017). This produced an estimate for above (trunks and branches) and below (roots) ground carbon of 5,140.3 tCO_2e and 4,671.2 tCO_2e respectively. This root:shoot ratio is uncertain and it is hoped that the University of Oxford study (destructive sampling) will provide greater confidence in the use of below ground root carbon in calculations (the recently published paper suggests a ratio of at least 1:1).[15]

According to Treeconomy's method of analysis, the area under new scrubby vegetation in 2022 in the Southern Block was 100ha, giving an average sequestration rate in the above-ground scrub of **2.7 tCO_2e ha-1 y-1** over the previous 19 years.[18]

Section 4:
Carbon sequestration on Knepp Estate

4.3.2 Method 2 – LiDAR + Photogrammetry analysis with Lingner et al. (2018) allometric equations undertaken by Queen Mary University of London (Appendix 2)

Queen Mary University of London undertook a study that analysed different methodologies for gathering woody biomass volumetric data. They compared widely available commercial drones to highly specialised and research grade drones and publicly available LiDAR datasets generated by the Environment Agency (EA). See Appendix 2 for the full report and comparison, which highlights the efficacy of widely available drones as a tool for land managers for monitoring biomass change.

In doing so, and as part of a long-term study[19] at Knepp Estate, QMUL also estimated above-ground scrub biomass and split that biomass into the different categories. They ran two sets of analyses; The first was an analysis of publicly available LiDAR datasets from the Environment Agency (EA), comparing data from 2001 and 2019, the second analysed the same data as Treeconomy generated by FlyThru in 2022. QMUL used a different methodology for analysis of the area, volume and biomass than Treeconomy along with a different set of allometric equations[20]. However, the net results of CO_2e sequestration are relatively close despite the differences in volumetric assessments.

Figure 12
Estimated changes in vegetation height for new scrub and expanded hedgerow areas 2001-2019

Using the EA datasets, QMUL estimated that a total of 2,072,609 m^3 of new woody biomass (3,710 tonnes) grew above ground over the course of 16 years (assuming no change between 2001 and 2003), with a breakdown of species composition included in Table 3 below.

New vegetation	Volume (m^3)	% of total new vegetation
Bramble Scrub	160,495	8%
Thorny Scrub	489,828	24%
Sallow Scrub	933,245	45%
Hedgerow	489,043	24%
Total	**2,072,611**	

Table 3
New Vegetation Estimates (2001 - 2019)

QMUL's second study used the photogrammetry and LiDAR data generated by FlyThru in 2022 and showed a volume of 1,957,712.5 m^3 of new scrubby vegetation (3,504 tonnes of woody biomass) over an area of 100.6ha and an additional 301,690 m^3 or 540 tonnes of expanded hedgerow vegetation. This results in a total additional above ground biomass of 4,044 tonnes (2003-2022) compared to 3,710 calculated using the EA 2019 data.

These volumetric and biomass calculations converted to tonnes of carbon (assuming a ratio of biomass to carbon of 0.5) suggests a sequestration of **7,421 tCO_2e** at a rate of **3.3 tCO_2e ha-1 y-1** over 119.1ha.[21]

The above figures do not include woody biomass in the roots underground (below ground woody biomass). As mentioned previously, this is being examined by the University of Oxford study underway at Knepp, looking specifically at the relationship between trees and shrubs that have been browsed by the free roaming herbivores and their roots underground. As QMUL point out in their report in Appendix 3.

> " *Coincident 3D structural modelling using remote sensing approaches and destructive sampling of scrub at Knepp to develop site-specific allometric equations to support above-ground biomass estimation are recommended.* "

The University of Oxford study will do exactly this and generate allometric equations for 5 different species of scrub, providing both the root:shoot ratio[15] and the true weight of carbon when compared to volume of biomass. This essential piece of research will further refine the above numbers and provide knowledge on a further pool of carbon being sequestered underground in the root systems.

	Treeconomy (2022)	QMUL (2019)	QMUL (2022)
Volume of new vegetation (m^3)	4,283,617.8	2,072,611	2,259,402
Area covered by new vegetation (ha)	100.5	127.0	119.1
Duration of growth (years)	19.0	16.0	19.0
Above ground biomass (using Lingner et al.)	-	3,710	4,044
Above ground biomass (using Axe et al.)	2,803.8	-	-
Total carbon sequestered (tC)	1,401.9	1,855	2,022
Total CO_2e sequestered (tCO_2e)	5,140.0	6,808	7,421
Average carbon sequestration rate (tCO_2e ha-1 yr-1)	2.7	3.4	3.3

Table 4
New vegetation estimates and carbon sequestration rates for Knepp from Treeconomy and QMUL

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Carbon sequestration on Knepp Estate

4.3.3 QMUL – Part 2. Assessment of low-cost aerial survey and 3D modelling methods for vegetation monitoring in rewilded landscapes. (Appendix 3)

Alongside their volumetric estimates of new scrub, QMUL also tested various ‘low cost’ methods for monitoring woody biomass and compared these against research-grade drones.

The two widely available low cost drones that were tested were the DJI Mini 2 UAV (£269) and the DJI Air 2S UAV (£719). They were flown across the scrub in a variety of scenarios (leaf-on and leaf-off), and models produced by QMUL comparing the datasets between the low cost options and the research grade UAV.

The sensors on both the DJI Air 2S and DJI Mini 2 are capable of producing Digital Surface Models (DSMs) with similar levels of vertical accuracy to the UAV LiDAR system with relatively low numbers of Ground Control Points (GCPs) (<10). The vertical accuracy improved with increasing numbers of GCPs and exceeded that of the UAV LiDAR system once 15 GCPs were utilised.[22] Therefore, the low cost options were most accurate during ‘leaf on’ conditions.

In summary, low cost UAVs can be an extremely effective method for baselining and monitoring woody vegetation. However, their models are strongly influenced by time of year and are only reliable during ‘leaf on’ conditions. They are also affected by the number of ground control points. Pilots and analysts should use the QMUL report (Appendix 3) to plan and structure their surveys.

Figure 13
Research Grade Riegl Ricopter UAV

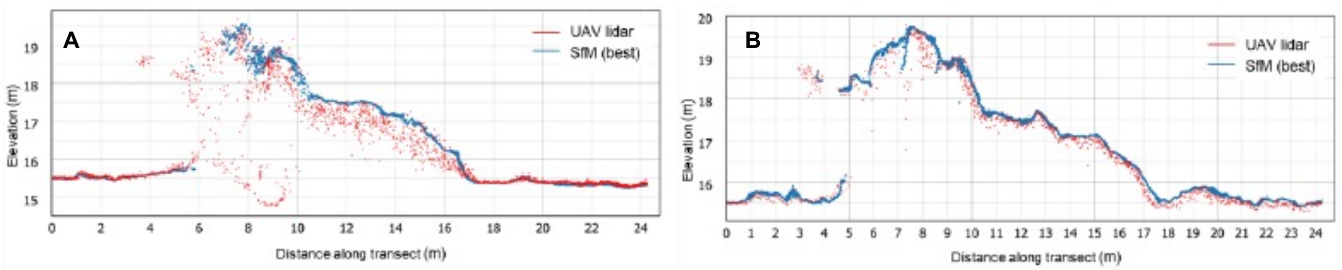

Figure 14
Comparison between LiDAR and SfM photogrammetric point clouds under A) leaf off, and B) leaf on, conditions. A) leaf off clearly shows a much less aligned comparison than B) leaf on.

4.3.4 Soils – Below-ground carbon analysis, undertaken by Agricarbon (Appendix 4)

Using stratified random sampling to determine coring locations, Agricarbon collected 2,260 samples from 639 cores across 94 ‘fields’ in the Southern Block in 2022. By statistically analysing the soil organic carbon (SOC) in these samples with a control site – an adjacent arable farm, with analogous soils and hydrology – a study by Helaina Black from the James Hutton Institute and Agricarbon has estimated that between **3.3 – 4.8 tCO_2e ha-1 yr-1** has been sequestered by the Southern Block’s ex-arable soils since 2003.[23] This is calculated by comparing soil carbon stocks between woodlands, grasslands, ex-arable areas (and the year they stopped farming), and arable fields all across the same soil type.

This range is significantly higher than the range of sequestration rates recorded in the existing scientific literature, which was outlined in Section 3. It confirms that soil carbon sequestration in process-led nature restoration projects is greater than in simple arable reversion to grassland, probably due to the impact of the large herbivores, which can amplify the biological recovery of soils through dunging, trampling and seed dispersal.

Taking the midpoint of the soil carbon estimated range (4.05 tCO_2e ha-1 yr-1) suggests that 356 hectares of ex-arable soils across the Southern Block have sequestered 28,836 tCO_2e since 2003. This does not include any sequestration that occurred in woodland or grassland soils within the Southern Block over that same time period.

Agricarbon’s analysis also showed that, even in 2023, the Southern Block’s ex-arable soils still had significantly less soil organic carbon (SOC) than soils under areas that were woodland or grassland in 2003 (see Figures 12 and 15). This suggests that the ex-arable soils have not yet reached carbon saturation and will continue to sequester additional atmospheric CO_2, eventually converging on the higher SOC levels found in woodland and grassland soils.

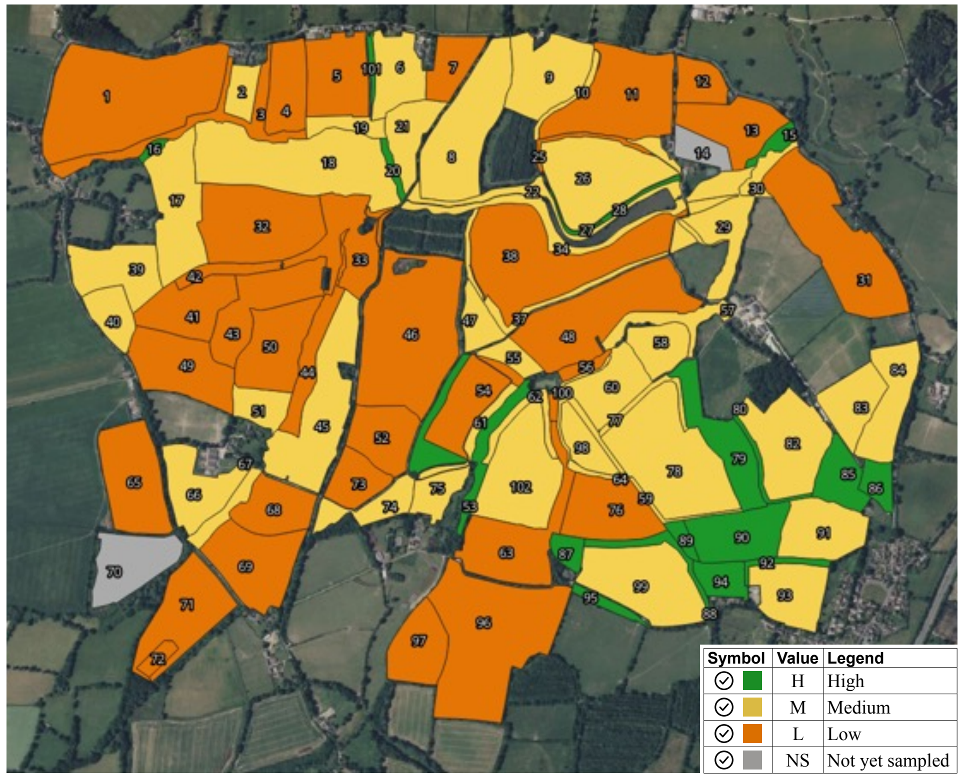

Figure 15
Agricarbon soil carbon baselining

Section 4:
Carbon sequestration on Knepp Estate

4.4 Discussion

The fieldwork undertaken for primary data collection from Knepp's Southern Block has generated robust estimates of both above and below-ground carbon sequestration rates for 'rewilding habitats' within a process-led nature restoration project. These are summarised in Table 5 below.

	Tonnes CO_2e sequestered above-ground	Tonnes CO_2e sequestered below-ground	Area (ha)	Duration (years)	Average rate of sequestration (tCO_2e ha-1 yr-1)
Treeconomy	5,140	-	100	19	2.7
QMUL (2019)	6,808	-	127	16	3.4
QMUL (2022)	7,421	-	119	19	3.3
Agricarbon	-	28,836	356	19	4.1

Table 5
Estimated above and below-ground sequestration rates for 'rewilding habitats' within the Southern Block

Of note, are the similar estimates of above-ground carbon sequestration proposed by Treeconomy and QMUL, despite different volumetric assessments of above-ground vegetation. This is largely due to the use of different allometric equations (Axe et al. vs Lingner et al.) for converting volumetric estimates into biomass and differences in the modelling of the vertical structure of vegetation in volume calculations.

Despite these differences, based on Agricarbon's analysis, it is clear that the average rate of below-ground sequestration is greater than the above-ground rate. In other words, it is carbon capture by degraded ex-arable soils that is having the greatest impact on 'rewilding habitats' ability to sequester atmospheric CO_2.

By combining Agricarbon's below ground carbon sequestration estimate with QMUL's longer duration estimate, it is possible to calculate a total carbon sequestration rate for Knepp's Southern Block over the past 19 years. This is shown in Table 6 below.

	CO_2e sequestered above-ground (tonnes)	CO_2e sequestered below-ground (tonnes)	Total CO_2e sequestered (tonnes)	Area (ha)	Duration (years)	Average rate of sequestration (tCO_2e ha-1 yr-1)
Southern Block (ex-arable land)	7,421	28,836	36,257	367	19	5.20

Table 6
Estimated total carbon sequestration rate for 'rewilding habitats' within the Southern Block

Given the paucity of literature available for 'rewilding habitats', as outlined in Section 3, the data in Tables 5 and 6 is hugely valuable. From them, this project can deduce five key insights:

1. 'Rewilding habitats' sequester and store large volumes of atmospheric CO_2 over at least their first 20 years of existence

2. The majority of carbon sequestration in 'rewilding habitats' is initially below-ground, in the soil. This corroborates evidence found in the scientific literature, highlighted in Section 3.

3. After nearly 20 years of carbon sequestration, SOC levels in ex-arable soils are not approaching saturation.

4. Over a 19-year duration, 'rewilding habitats' sequestration rates (**5.20 tCO_2e ha-1 yr-1**) are of a similar magnitude (~86%) to those estimated by the Woodland Carbon Code's calculator for a new native woodland (**6.05 tCO_2e ha-1 yr-1**) (Table 1).

5. The root:shoot ratio determined by Burrell et al. (2024) at Knepp implies that a roughly equal amount of biomass exists below the scrub and hedgerows as was measured above ground. If this is correct, then sequestration rates within the Southern Block are significantly higher than suggested in (4) above and likely greater than 6.20 tCO_2e ha-1 yr-1.[15]

In addition to these insights, the Knepp Wildland Carbon Project was also able to test several approaches to data collection, proving ultimately that carbon sequestration and storage in 'rewilding habitats' can be baselined and monitored over time.

Taken together, these discoveries strenghten the case for the inclusion of 'rewilding habitats' in the VCM. Process-led nature restoration projects tend to secure better outcomes for biodiversity than woodland creation projects that are delivered solely through tree planting. Given that the 'rewilding habitats' produced through process-led nature restoration are also sequestering significant volumes of atmospheric CO_2 over at least 20 years, it is likely that they represent a more resilient nature-based solution to new woodland creation on poor-yielding ex-arable land; an approach that potentially addresses the climate and biodiversity crises more comprehensively.

If this assertion is valid, then policymakers and practitioners should look to create the necessary market infrastructure and plug remaining data gaps so that 'rewilding habitats' can generate certified carbon credits in the future and access new sources of revenue from ecosystem markets.

Data gaps do, however, remain; the allometric equations between volume of open grown scrub, tonnes of biomass and carbon together with the root:shoot ratios of scrub and their roots. Whilst this project provides strong estimates, the data gaps being filled by the University of Oxford will be crucial to build further confidence and specificity around rewilding habitats and carbon. Early results point towards the fact that root biomass is likely to add at least the same amount of woody carbon again, suggesting the rates set out in this report are lower than the true rates of sequestration.

Greenhouse gas and carbon flux of the ecosystem is another area that needs further study. Exeter University through the Net Zero Plus Project, have erected a flux tower at Knepp and a neighbouring control site (amongst other sites in the country) to measure the flux of greenhouse gasses in theses differing systems. This will inform beyond the amount of carbon stored in the soils and scrub, but the gas exchange and net draw down on an annual basis.

05
Routes to market

Section 5: Routes to Market

Key driver for this project

To understand the potential for generating certified carbon credits from 'rewilding habitats' within the context of the UK voluntary carbon market

5.1 Introduction to the Voluntary Carbon Market (VCM)

In light of the climate crisis, many businesses and corporations have set themselves the objective of being 'net zero' with respect to their greenhouse gas (GHG) emissions by a certain future date, for instance 2040. To achieve this will require a reduction in the emissions they produce, with any residual emissions compensated for through direct carbon removal from the atmosphere.

Many businesses are unable to remove atmospheric CO_2 themselves and so will purchase these removals as a type of carbon 'offset'. To facilitate the generation and sale of offsets, a voluntary market has emerged in which financial instruments known as carbon credits are traded, each of which is equivalent to one tonne of atmospheric carbon dioxide equivalent (1 tCO_2e). This market is known as the VCM, to differentiate it from existing GHG compliance markets that some governments have created.

To provide their stakeholders with assurance around net zero claims, many businesses have aligned themselves to the Science-based Targets initiative (SBTi), which provides clarity and guidance around what being net zero means in practice (Figure 16).

As the demand for climate action increases, the VCM continues to grow and is projected to continue doing so. According to the Taskforce on Scaling Voluntary Carbon Markets (TSVCM), the demand for carbon credits could increase 15-fold by 2030 and a 100-fold by 2050, resulting in a global carbon credit market worth more than $50 billion in 2030.[24]

Key components of the Corporate Net-Zero Standard

1. Near-term targets

Rapid, deep cuts to direct and indirect value-chain emissions must be the overarching priority for companies. Companies must set near-term science-based targets to roughly halve emissions before 2030. This is the most effective, scientifically-sound way of limiting the global temperature rise to 1.5°C.

2. Long-term targets

Companies must set long-term science-based targets. Companies must cut all possible emissions - usually more than 90% of emissions before 2050.

3. Neutralise residual emissions

After a company has achieved its long-term target and cut emissions by more than 90%, it must use permanent carbon removal and storage to counterbalance the final 10% or more of residual emissions that cannot be eliminated. A company is only considered to have reached net-zero when it has achieved its long-term science-based target and neutralised any residual emissions.

4. Beyond Value Chain Mitigation (BVCM)

Businesses should invest in BVCM in addition to near- and long-term science-based targets. BVCM includes projects to restore natural carbon sinks like tropical forests and peatlands as well as projects that protect nature such as Jurisdictional REDD+. It also includes technology based removals such as Direct Air Capture and Carbon Storage. BVCM is never a substitute for rapid and deep cuts to value-chain emissions.

Figure 16
Science Based Targets.[25]

Section 5:
Routes to Market

5.2 The UK Voluntary Carbon Market

Within the UK, the generation and sale of nature-based carbon credits has been enabled by the creation of two domestic carbon standards, the Woodland Carbon Code (WCC) and the Peatland Code (PC). The government-backed codes provide the standardisation, quality assurance and integrity that a market requires, including third-party verification of any accredited projects.

Generation and sale of carbon credits under these codes is creating new revenue streams for land managers that are able to create new woodland and restore peatland, respectively. As the VCM grows, other standards are emerging so that a greater range of nature-based solutions can be (partly or wholly) financed through the carbon market.

Currently, there is no specific UK carbon standard for process-led nature restoration projects, despite the clear climate benefit these projects can provide (as outlined in Section 4). In the following sections, this project considers what the existing barriers within the market are and how they might be overcome.

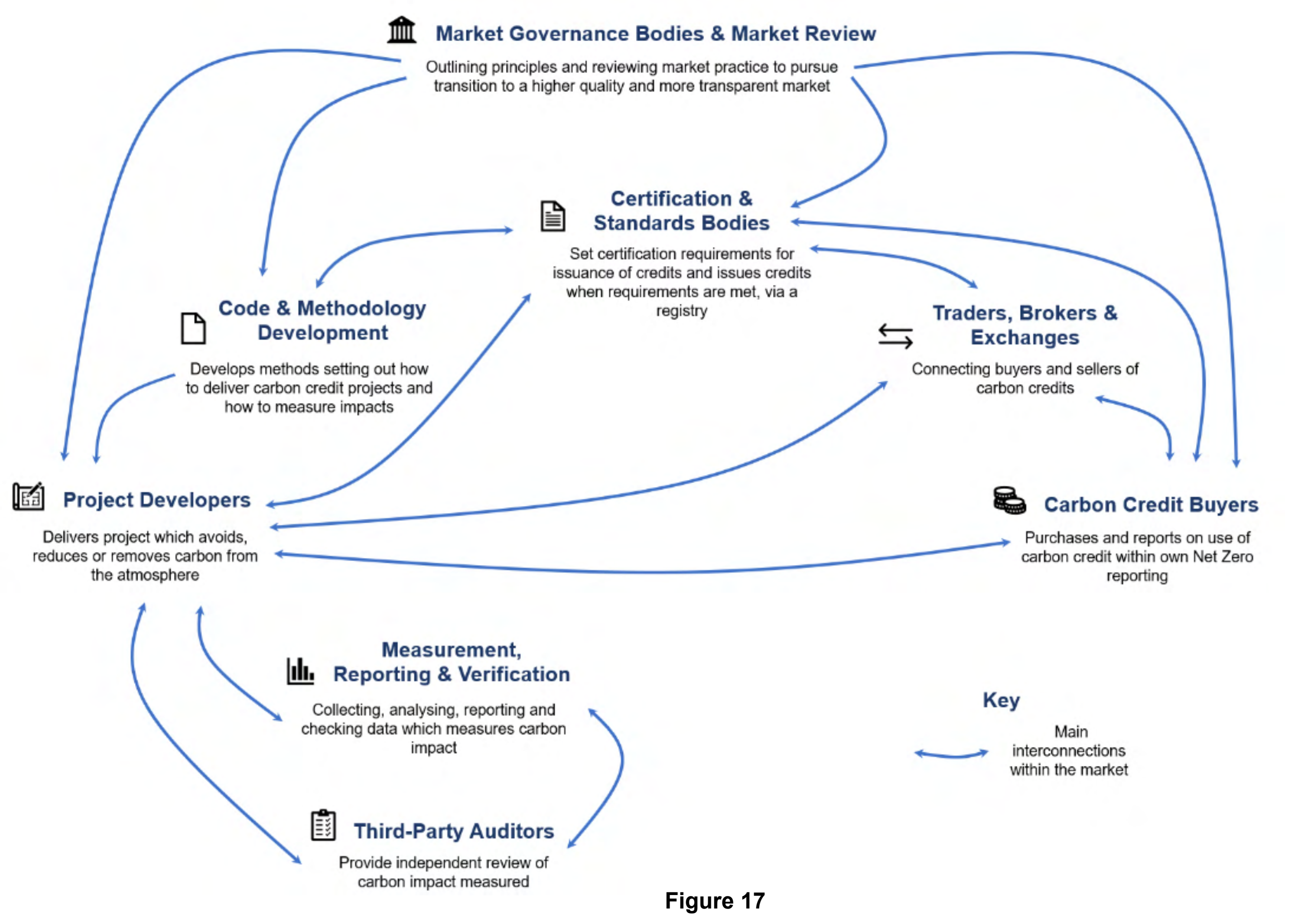

Figure 17
A schematic highlighting the main components of a voluntary carbon market

5.3 Barriers within the market

There are a range of barriers within the existing UK VCM that prevent process-led nature restoration projects from generating certified carbon credits. These include:

- Lack of appropriate carbon standards for nature-led projects.
- Additionality, stacking and bundling policy. There is a lack of clarity on future policy around stacking and bundling of ecosystem services.
- A lack of robust datasets for ‘rewilding habitats’ has meant predicted carbon models for codes and standards do not accurately or fully represent sequestration rates from rewilding projects.
- A carbon price that does not fully reflect the biodiversity benefits and additional ecosystem services of process-led nature restoration.

5.4 Existing routes to market for ‘rewilding habitats’

As part of this report, an analysis of the existing routes to market for nature based solutions has been undertaken to understand their applicability to rewilding. A summary of the key findings are reported in the following tables.

Section 5:
Routes to Market

5.4.1 Woodland Carbon Code

Table 7 below provides an overview of the Woodland Carbon Code.

	Woodland Carbon Code
Overview	The Woodland Carbon Code (WCC) is a quality assurance standard for woodland creation projects in the UK. It is a UK Government backed scheme, which aims to provide high integrity independently verified carbon units.
Available services	Project validation, verification of units, project guidance.
Relevance to rewilding scenario	WCC do accept natural regeneration of woodland as projects within the scheme, as long as the final output of the project is an established woodland. However, a scrubby successional habitat mosaic scenario may not meet the requirements. Although there is no current methodology within the WCC that is directly applicable to rewilding, their website states they are accepting new methodologies which can be piloted – therefore more relevant opportunities may arise in the future.
Monitoring requirements	Verification is needed in year 5 of the project, and every 10 years subsequently.
Pros	WCC is a well-established standard within the UK. It is also relatively cost effective compared to other market players. It is backed by the UK Government and the potential carbon sequestration can be modelled for free using a relatively straightforward carbon calculator. No similar tool is available specifically for rewilding and nature recovery projects.
Cons	WCC currently has very low soil carbon estimates (compared to data gathered as part of this NEIRF project), and the estimates are only applicable to woodlands.

5.4.2 Wilder Carbon

Table 8 below provides an overview of the Wilder Carbon Standard.

	Wilder Carbon
Overview	Wilder carbon has been developed by an association of wildlife charities led by the Kent Wildlife Trust with the purpose of funding rewilding projects delivered in the UK through the generation and sale of nature rich carbon credits. Wilder Carbon has developed a mechanism to allow for the sale of carbon credits from rewilding projects, including buyer approval process, legal procedures for purchase of credits, a credit registry and a standard which outlines how projects can develop carbon credits for sale. The credits can be created from a range of carbon rich habitats, where minimum intervention management is used to restore natural habitats. Therefore, on top of carbon sequestration, biodiversity uplift is achieved and evidenced, leading to wider ecosystem services being achieved such as flood management.
Available services	– Wilder Carbon Standard for Nature and Climate enables the certification of approved projects and ensures projects can be matched with ethical credit buyers and investors. – Trusted Deliverers – the landowner on which a Wilder Carbon project aims to take place. – Estimated Issuance Units (EIUs) and Verified Carbon Units – units can only be purchased from Approved Buyers who meet the ethical and sustainable standards of Wilder Carbon. – Trusted Monitoring and Verification Partners – ensure projects meet or exceed levels of carbon removal or reduction, and biodiversity gain over the project lifetime.
Relevance to rewilding scenario	Wilder carbon allows for the sale of rewilding credits within the UK, across a variety of rewilding habitats including creation of woodland, wood pasture or wood/ scrub mosaic primarily through natural regeneration from arable or grassland with low to medium carbon levels; arable reversion to species-rich semi-natural grassland on soils with low to medium carbon levels (other habitats such as peatland, mudflats and bogs also included in Wilder Carbon's portfolio).
Monitoring requirements	Commit to maintaining habitats restored through Wilder Carbon finance for a minimum of 50 years (ideally 99 years as this is classed as being in perpetuity). Monitoring to be completed 6 to 12 months prior to periodic verification throughout the project. The baseline methodology used in this study would be permissible.
Pros	Allows for the sale of rewilding carbon credits by having a more flexible methodology and standard than some of the other carbon credit providers. In addition, it includes a quantification of biodiversity and ecosystem services benefits within the carbon credit. Wilder Carbon only allows Approved Buyers to purchase credits through them, ensuring only companies with ethical practices and those that have an active commitment to reach net zero. The carbon price of of Wilder Carbon's Carbon+ credits is also higher than many other providers on the market at £75 per tonne CO_2.
Cons	The main and driving reason that Wilder Carbon is not yet scalable is the current soil carbon estimates are incredibly low compared to the data revealed in this NEIRF project. In addition, scrub habitat has to have a 40% buffer applied, further reducing the value for estimated carbon sequestration. The high buffers and conservative estimates of sequestration currently restrict commercial opportunity, particularly for projects requiring significant advance financing. Wilder Carbon is young and therefore untested and currently only operates in the UK.

Section 5:
Routes to Market

5.4.3 *Verra*

Table 9 below provides an overview of the Verra Standard.

VERRA	**Verra**
Overview	Verra is an internationally recognised carbon standard, who are directly responsible for around three-quarters of all voluntary carbon credit transactions. As such, they have a large international buyer pool and are very well known within the market.
Available services	– They provide standards for a variety of carbon sequestration projects related to agriculture, forestry and other land use (AFOLU), including Afforestation, Reforestation and Revegetation (ARR); Agricultural Land Managament (ALM); Improved Forest Management (IFM) and Avoided Conversion of Grasslands and Shrublands (ACoGS). – Methodology development for different types of carbon reduction or removal projects. – Verra registry – where information on registered projects and projects within the registration pipeline can be found, including data on issued and retired units, information on units available for trading, and all documentation and information related to each project. – Verification and validation – Verra facilitate the validation and verification of projects by independent third-party auditors known as validation/ verification bodies.
Relevance to rewilding scenario	Verra have released a new methodology for their Afforestation, Reforestation and Revegetation (ARR) category which would be compatible with rewilding projects that include scrub, wood pasture and woodland.
Monitoring requirements	Specific monitoring requirements are dependent on which category from Afforestation, Reforestation and Revegetation are chosen. In general, the ARR methodology requires calculation of baseline emissions and calculation of project emissions to include carbon stocks from above ground woody biomass, above ground non woody biomass, below ground woody biomass, below ground non woody biomass. The baseline methodology used in this study would be permissible.
Pros	Well-known in the industry, and has a relevant methodology for rewilding habitats. Verra has a generalised credit buffer pool to account for natural risks, internal management risks and external risks related to carbon sequestration projects.
Cons	Can be extremely expensive. Project development can be complicated without the guidance of an experienced project developer (which is another added expense). New ARR methodology is not well established and requires projects to be developed over a large area to ensure cost effective returns.

5.4.4 *Emerging codes and standards*

There are a range of codes and methodologies currently under development which could benefit specific habitat creation projects and regenerative agricultural practices, however, they are not directly aligned with process-led nature restoration:

- The **UK Saltmarsh Code** is being developed by the UK Centre for Ecology and Hydrology. The aim of this code is to be able to market and trade carbon credits from the restoration and creation of saltmarsh.
- The **Hedgerow Carbon Code** being developed by the Allerton Research & Educational Trust. This code will lead to the creation of carbon credits from hedgerow restoration.
- The Forestry Commission are exploring a **Woodland Water Code** for development by 2025, which would provide a standard for water-related nature-based solutions to woodland creation, such as flood risk mitigation and pollution alleviation.
- Ecometric have developed a **HGH benefits in Managed and Grassland Systems Credit Class** on the Regen Network registry. The focus is on soil carbon in farms converting to soil regenerative practices, therefore would not include above ground biomass synonymous with rewilding projects.
- The **UK Carbon Code of Conduct** provide a set of standards for soil carbon and regenerative agriculture to drive investment into nature-based solutions. The set of standards will mainly be applicable to regenerative farming systems, however, they are developing habitat-based models and credits. This is therefore a potential route to market, but it is lesser known and has less strict monitoring requirements than other standards.

5.4.5 *Carbon rating schemes*

Carbon rating schemes have emerged within the market to provide a third party review of carbon credit claims. The ratings can help buyers understand the risks associated with credits from a specific project. But they also benefit land managers by providing an extra layer of integrity to credits from their projects.

Using carbon rating schemes could be one way to foster the sale of credits through lesser-known standards and codes such as Wilder Carbon or the UK Carbon Code of Conduct. If a project has a good rating, buyers may feel confident enough to purchase credits through newer mechanisms on the nature and carbon markets.

The two market leading carbon rating schemes are listed below:

- **Sylvera**: are a carbon credit ratings organisation who review VCM carbon credit project credentials using project data, machine learning and multiple types of satellite data to provide an overall carbon credit quality rating. Sylvera defines a high-quality carbon credit as 'a unit representing one tonne of CO_2 emissions avoided or removed from the atmosphere for an environmentally significant period of time, as a direct impact of project activities'.
- **Be Zero Carbon**: BeZero are a carbon ratings and risk analytics organisation that allocate BeZero Carbon Ratings (BCR) to projects within the VCM. The BCR represents BeZero Carbon's current asessment on the likelihood that a given credit achieves a tonne of CO_2e avoided or removed. The BCR is conveyed using an 8-point scale, from highest likelihood to lowest likelihood.

Section 5: Routes to Market

5.5 Evolving Market Mechanisms

5.5.1 Growing interest from Government

In recent years, the UK Government has increased the output of publications and policies related to nature and carbon markets. A recent report on financing nature recovery in the UK found that the current finance gap for nature recovery is £5.6 billion a year in the UK alone.[31] Despite needing a lot of progress to reach this funding gap, policy around private nature finance is evolving:

- The 2023 Green Finance Strategy[32] aims to position the UK as a world leader on green finance. Its aims include: growing UK green finance services, increasing investment in the green economy, creating financial stability by reducing climate risk through investment, incorporating nature and climate resilience into financial markets and aligning with global objectives on climate change and nature.
- The British Standards Institute are currently working on the Nature Investment Standards Programme; a consensus based, UK-wide standards framework for high integrity nature markets. The key objectives of the BSI programme are to: scale high integrity markets to enable trade in ecosystem services; support flow of private sector investment; provide confidence in the market and protect against greenwashing, and accelerate nature recovery.
- The UK 2030 Strategic Framework for Climate and Nature[33] outlines how emissions will be reduced, nature loss reversed and climate resilience will be built into the economy, both within the UK and globally.

5.5.2 Stacking and bundling

Stacking is when units or credits from different ecosystem services can be issued separately for an intervention on the same piece of land. For example, carbon and biodiversity could be sold separately from 'rewilding habitats' that develop on the same piece of land. Stacking is beneficial because it encourages multi-functional land use by allowing multiple ecosystem services to be monetised simultaneously. It also means those projects that work to maximise multiple ecosystem services are justly rewarded for that work.

Bundling occurs when different ecosystem services are bundled into a single unit or credit and sold as one unit. For example, carbon credits with biodiversity benefits included. Bundling can encourage the market to increase the price of carbon credits. Using the example above, carbon bundled with biodiversity benefits could be sold as a premium carbon credit, and therefore achieve a higher price per credit. Credits issued from the Woodland Carbon Code and Peatland Code are known as implicit bundles, whereby the wider benefits of woodland creation or peatland restoration is included in a non-quantified form along with the quantified carbon.

Currently, stacking and bundling are constrained by a few factors including; limited availability of suitable methodologies to allow stacking and bundling, infancy of nature markets compared to the more established carbon market, lower current demand to pay a premium for stacked and/ or bundled credits and additionality concerns. The UK Government has outlined that in the current phase, voluntary credits such as carbon may only be stacked with statutory units such as Biodiversity Net Gain when the related habitat improvements for the voluntary credits is delivered on top of initial activity related to the statutory units and does not negatively impact the outcome of the statutory scheme . The government will consider the implementation of a greater degree of stacking at a later phase. Further stacking of other nature-based benefits, such as biodiversity and water with carbon, is currently being investigated.[31]

5.5.3 Carbon plus credits

Carbon plus credits have recently emerged as a new derivative of standard carbon credits. Within a carbon plus credit, other benefits such as biodiversity uplift are 'bundled' in with the carbon credit, creating a premium product. This type of carbon credit could be sold for a higher price, as buyers could use the bundled biodiversity uplift as part of their Environmental, Social and Governance (ESG) targets without having to purchase separate biodiversity credits. Wilder Carbon are a good example of the Carbon Plus credit model.

5.6 Conclusion

The VCM within the UK is growing and changing rapidly, but still lacks the scope to be able to finance varied and wide-ranging habitat restoration projects through carbon credit transactions. To progress the market to support rewilding projects, a number of existing barriers much be addressed.

Firstly, actors within the VCMs should support the development of new data and research to support the codes and standards that cover a wider range of habitats and processes, such as rewilding. A key supporter should be the UK Government, who are beginning to progress this with the development of new codes for saltmarsh, hedgerows and water woodland credits, and should continue to widen its support.

Underpinning these new codes and standards need to be robust methodologies, which accurately enable the prediction of both above and below ground carbon sequestered through rewilding schemes. This should be supported by the collection of baseline data, such as that contributed by this NEIRF project.

Landowners or potential project developers face multiple financial barriers when considering delivery of a rewilding scheme. These barriers include upfront costs of delivering the project on the ground, in addition to high verification, baselining, monitoring and certification costs. As has been delivered through existing codes such as WCC and PC, consideration should be given to financial incentives that can overcome these issues, such as grant schemes and subsidised verification and certification costs.

The current barriers to stacking and bundling also cause an added layer of complexity when considering the VCM as a potential finance mechanism. Project developers are required to only select one form of ecosystem service finance, which can result in limited financial gain and less integrated benefit delivery. The UK Government should consider the potential benefits to nature finance if stacking and bundling was promoted.

In addition to supporting the supply side of the market for rewilding projects, more can be done within the field of rewilding to ensure the multiple benefits of rewilding are monitored and recorded, so that these can be promoted to potential buyer organisations.

06

Boothby Wildland: A Case Study

Section 6:
Boothby Wildland: A Case Study

Key driver for this project

To create a guide, using Boothby Wildland as a case study, for UK nature restoration projects wanting to understand their carbon stocks and the potential sequestration through a robust approach to baselining and monitoring, reporting and verification.

6.1 Boothby Wildland

The following section outlines the approach that a process-led nature restoration project, Boothby Wildland, in Lincolnshire, has followed to allow for the generation and sale of natural capital products, such as carbon credits. No two nature restoration projects are the same and so the process outlined below should be considered as a guide for other practitioners to consider rather than a template that can be replicated. Carbon and other ecosystem markets are nascent and still evolving, so it is likely that the technologies, methodologies and products themselves will continue to change in the future.

Boothby Wildland was purchased in December 2021 by Nattergal Ltd., for the purpose of process-led nature recovery. The ambition is to fund the project through the sale of natural capital products and/or payments for ecosystem services. Boothby is highly-suited to process-led nature restoration, being comprised of variable clay-based soil types with lower agricultural productivity (agricultural land classification: Grade 3a and 3b), a low natural capital baseline and a suitable scale for natural processes to properly function with minimal human intervention. Farmed in a very high input arable system for over half a century, Boothby was producing average yields of crops largely used for animal feed. Through 2022 and 2023 Boothby Wildland was baselined for natural capital, with biodiversity, carbon, water quality and soil health all assessed to understand how the site's ecological health can be enhanced and what natural capital outputs it is best suited to producing.

6.1.1 Natural Capital

As the team at Nattergal continue to explore the best means for funding process-led nature restoration through the sale of ecosystem services at Boothby, they have grappled with three central questions:

1. What ecosystem services are likely to be enhanced by process-led nature restoration at Boothby?
2. How can those ecosystem services be packaged up as a natural capital product to generate revenue for the project?
3. How can the true value of these enhancements be realised?

In the absence of existing protocols for generating natural capital products from process-led nature restoration, Nattergal decided to follow a similar approach to baselining to the one set out in Section 4, which was used at Knepp. Boothby Wildland had the potential to generate products for the voluntary carbon market, statutory biodiversity market and, potentially, future nutrient neutrality and voluntary biodiversity markets too, meaning that a broad and comprehensive baselining would be required.

6.2 Pre-project considerations

A crucial initial consideration for any process-led nature restoration project is to assess if rewilding is an appropriate land use for the proposed project area. While nature recovery is essential, the UK also requires land to grow food and fibre, generate renewable energy, provide space for recreation and regulate air and water.[34] As a result, some areas of land will be better suited to process-led nature recovery than others and it is vital that 'rewilding habitats' are targeted onto appropriate sites.

Assuming a parcel of land is suitable for process-led nature restoration, the following factors must then be considered:

- Additionality: is the project additional or is it already committed to the land use change through a legal requirement. (i.e. in an agri-environmental scheme, a biodiversity net gain (BNG) contract or a SSSI). If the project is not additional, the carbon gains are unlikely to be certifiable and tradable.
- Permanence: If positive ecological changes are realised, how can they be maintained and safeguarded in perpetuity?
- Potential: Does the land have good potential for enhancing ecosystem services or is it already functioning well, from an ecological perspective?

  – For example, a site that has been in regeneratively managed pasture or arable may have relatively high soil carbon stocks already, lessening its potential for revenue-generating carbon sequestration
- Monitoring, reporting and verification: If the land has potential for enhancing ecosystem services, how will that uplift be captured, reported on and verified?

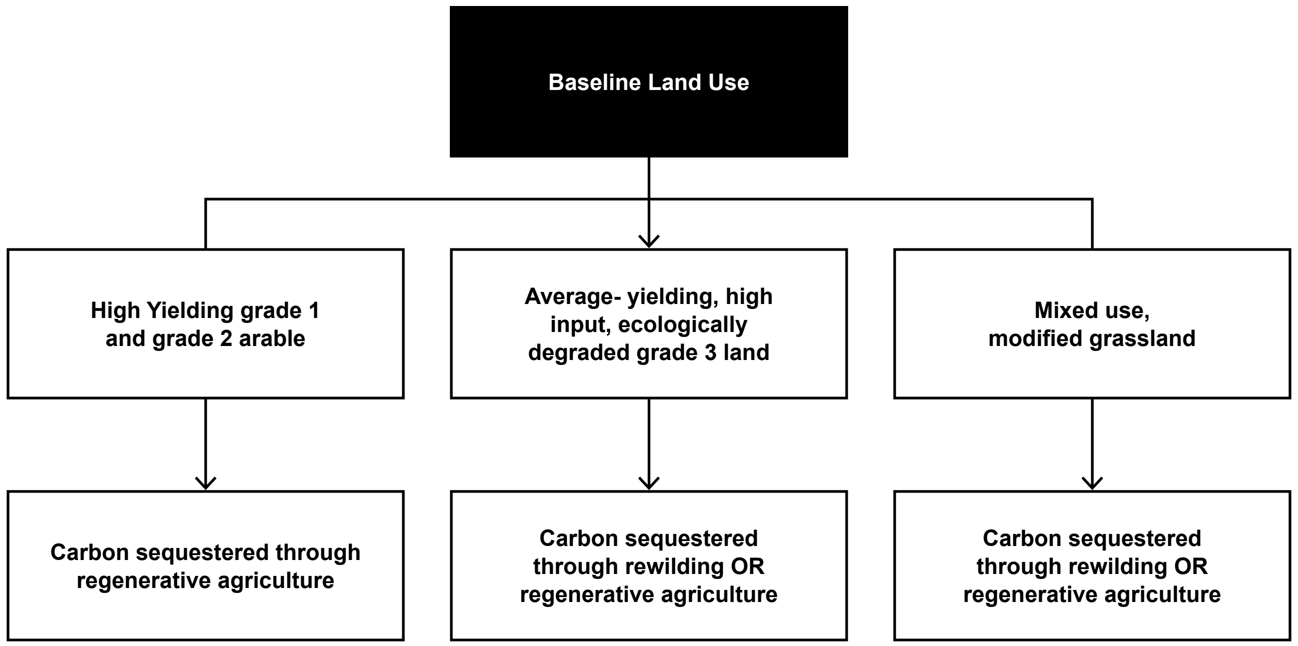

Figure 18
An approach to rewilding

Section 6:
Guide and Case Study

6.3 Project Development

6.3.1 Baselining the project area

The baseline provides the reference point to measure future ecosystem service delivery against. There are a multitude of actors in the voluntary carbon market offering baselining solutions ranging from satellite-based technologies to soil coring and lab analysis. This guide cannot discount or confirm all suppliers in the market but suggests a potential decision tree for deciding how to baseline.

Round 1 of NEIRF funded the UK Farm Soil Carbon Code, which reached a similar conclusion; developing a code or standard is beyond the scope of the NEIRF grant. They did, however, develop a 'minimum set of requirements' for soil carbon baselining and monitoring. We use and reference this set of requirements as Appendix 4 and 5 rather than replicating our own system for baselining soils. One key difference for rewilders to consider compared to 'regenerative farmers' is soil depth. The minimum set of requirements highlights 30cm as a minimum, and between 30cm-60cm as recommended, however, measuring carbon at depth can be very important for measuring change in rewilding projects. At Boothby, the measurements were taken down to 1 metre depth wherever possible.

6.3.2 Above-ground biomass

Q1. Ignoring existing woodlands, do you have woody vegetation established on the site already?

a) No, the project is across grassland or arable land. Your baseline is zero and there is no woody biomass just as with a tree planting project. It is important to save this baseline as a point in time. Question 2 (Q2) addresses the best methodology for doing so.

b) Yes - but only hedgerows. Your baseline is still effectively zero because the bulk of the regeneration will be on the land between the hedgerows. However, it is important to save this baseline and the size of the hedges as the starting point, so as they fall out of management and grow larger, with any additional biomass being measurable (as demonstrated in the QMUL and Treeconomy analysis). Q2 addresses the best methodology for baselining.

c) Yes – there are significant areas of scrub, trees and woody biomass outside of hedgerows and existing woodland. It is very important to capture the areas that already have woody biomass, to either exclude them from calculations or to measure additional changes in growth from the baseline.

At Boothby Wildland, the answer was (b). Approximately 85% of the site is arable meaning Boothby is in theory easy to baseline. If you ignore existing woodlands and hedgerows, the baseline for woody biomass is zero. It is, however, important to baseline the existing woodlands and hedgerows, so that they can be excluded from calculations or growth in woody biomass can be calculated over time as young woodlands grow taller and unmanaged hedgerows grow wider. Nattergal saved multiple publicly available datasets, using EA LiDAR and satellite images. However, they also chose to commission a drone flight for higher quality LiDAR and photogrammetry.

Q2. How to baseline woody biomass?

Firstly, satellite images and open source LiDAR datasets generated by the EA do provide a very strong baseline if they are recent and of good quality. However, it is always worth gathering your own data to compare against.

a) If the project is 150ha or less. Your site is likely small enough to manually baseline using a commercially available low-cost UAV (or drone). As demonstrated by the QMUL study (Appendix 3), commercially available drones are an excellent and accurate tool for capturing a baseline. This can either be bought and self-flown or a drone pilot can capture this for you. As highlighted by the QMUL research, you should ensure that this survey is done 'leaf-on' and has an adequate number of ground control points. A drone will cost anywhere between £300-£3,000.

b) If the project is between 150ha – 1,000ha. A self-flown drone is likely to take too long. There are multiple drone flight services who will baseline the site producing both photogrammetric data and LiDAR. This can be expensive; depending on the size of the project, it will range between £3,000 - £15,000.

c) If the project is >1,000ha. Satellite imagery is likely to be most cost effective for very large sites. However, drone-generated data is preferable where budget allows, due to its higher resolution, and can be used to ground truth certain areas and extrapolate out. Working with landscape scale GIS and remote sensing companies is the best route forward for projects of this size.

Boothby Wildland is 617ha. Nattergal baselined the site using LiDAR and Photogrammetry and worked with Treeconomy to calculate the carbon stocks in the existing woodlands and hedgerows. However, given the carbon sequestration is going to take place across the ex-arable land, this was the only crucial area needed for the baseline. Satellite and EA LiDAR may have been enough. Nattergal worked with Treeconomy to analyse the drone gathered data and to understand existing carbon stocks in woodlands and hedgerows.

Q3. What to do with the data?

LiDAR or photogrammetric data on its own can generate huge datasets and unless a specialist is employed, who can analyse the data accurately and efficiently, these datasets are very difficult to interpret. At Knepp and Boothby Wildland we have worked with QMUL and Treeconomy however, in the case of rewilding projects around the country other universities and companies may be more suitable. At this point, generating the data and holding it is the critical element, as it can always be referred to over time. The analysis of the data may only be required further into the project and will need to be completed by specialists such as QMUL or Treeconomy.

At Boothby Wildland, Nattergal worked with Ace Nature to store our data and Treeconomy to analyse and produce a baseline report and summary.

Summary – Above Ground Biomass (AGB)

Depending on the size of the project, there will always be a need to work with specialists to gather and interpret the baseline and monitoring data. However, if you assume that most rewilding projects start from an intensive form of land use with few trees or shrubs, then in essence the baseline is easy – it is zero. The challenge is to find the data that shows this and to save this as a point in time, best achieved through drone flights and satellite data. Where specialist companies and academic institutions play a critical role will be in analysing that data against future surveys to demonstrate volumetric changes.

Section 6:
Guide and Case Study

6.3.3 Soil carbon baselining

It is recommended to use the UK Sustainable Soils Alliance minimum set of requirements to best understand how to baseline the soil. The MRV protocol is set out in their "Report and recommendations on minimum requirements for high-integrity soil carbon markets in the UK" in section 2.3 (Appendix 4 and 5 to this report).

At Boothby, Nattergal worked with Agricarbon, and there were critical elements of the baseline that were able to be captured through Agricarbon's methodology;

a) Measurement at depth. Agricarbon measure down to 1 metre. This is potentially crucial as we learn more about how deep rooting scrub and plants and biologically healthy soils take carbon deeper and deeper.

b) Measured not modelled. Whilst modelling plays a very important role in estimating sequestration potential, Nattergal thought it important to ground their models and future claims in tangible measurements. The density of data will also allow Nattergal to contribute to scientific literature in due course and further improve the data produced through this study as Boothby Wildland gets progressively wilder.

c) Comprehensive. Due to a lack of certainty in the market around 'MRV', Agricarbon's methodology was felt to be amongst the most comprehensive and it would fit into whichever accreditation scheme emerges as the leading methodology.

6.4 Verifying your carbon

As outlined in Section 5 of this report, the voluntary carbon market is not yet able to support truly process-led, multi-habitat projects. The data generated through this report is likely to change this, however, and below we highlight potential routes to market, including Nattergal Ltd.'s approach at Boothby Wildland.

Wilder Carbon

Wilder Carbon is a carbon certification and registry system specifically designed for rewilding habitats and biodiversity-led nature based solutions. Unfortunately, up until now, the carbon sequestration modelling associated with grasslands and scrublands has been low in confidence and underestimated the value of wood pasture and scrubland habitats. With the research now available through this report, Wilder Carbon becomes an excellent option for delivering rewilding projects through certifying and trading carbon.

Wilder Carbon is young and relatively unknown compared to the Woodland Carbon Code and Peatland Code. As data improves and confidence in predicted carbon sequestration models grows, we expect Wilder Carbon to grow as a certification body.

At Boothby, Nattergal will be revisiting Wilder Carbon as an option as and when the data in the rewilding habitat models improves and reflects the results of this report.

Woodland Carbon Code

Natural colonisation or natural regeneration through the Woodland Carbon Code remains an option for rewilding projects. However, they require the project to aim for woodland creation and by definition would require the exclusion of browsing and grazing herbivores, meaning a more homogeneous set of habitats and not a true 'rewilding' project. Natural regeneration and colonisation projects do, however, have strong biodiversity benefits (as opposed to planting) and should be encouraged.

At Boothby, Nattergal are likely to use the Woodland Carbon Code for a natural colonisation woodland creation project in a field set away from the main rewilding area by a road.

Verra

Verra hosts a set of global standards for climate action and sustainable development. Whilst there have been multiple examples recently of Verra being criticised in the media, these have been for 'avoided loss' projects. Rewilding projects are not avoided loss, but rather carbon removals. Verra has a new methodology launched in September 2023 called Afforestation, Reforestation and Revegetation or ARR. This methodology aims to support multiple systems of establishing new vegetation and for the first time includes the option to include below ground soil carbon simultaneously to AGB – one of the prohibitive blockers to most certification schemes for rewilding.

At Boothby, unfortunately, Verra is prohibitively expensive for 'small' projects. To be commercially viable, Verra requires huge areas to get the scale where the return on investment would justify the certification costs. Nattergal expects to add multiple sites to its portfolio, joining Boothby and therefore will continue to explore the ARR methodology as part of a wider and more collective approach. This could be a solution for rewilding clusters or networks, where collaboration may enable market access.

6.5 Costs and financial barriers

The carbon baseline and analysis at Boothby cost £27,000, approximately £10,000 on above ground biomass and £17,000 on soil carbon.

This is clearly a high upfront cost. However, it should be noted that Nattergal went above and beyond to secure the most in-depth baseline possible. In part due to the lack of clarity around MRV requirements in the market and in part due to the fact Nattergal aims to contribute to furthering scientific literature and a better understanding of sequestration rates in degraded soils.

As highlighted in Section 4 and in the minimum set of requirements set out by the Sustainable Soils Alliance, it should be possible to baseline a 600ha site for substantially less than this and it is likely that costs will continue to fall in the future.

Evidence suggests that Wilder Carbon is pricing its carbon at £75 per credit. If the carbon figures produced in this report are used to model Boothby, this means that on the 530 hectares of ex-arable land, it could be expected to achieve **5.2tCO_2e ha-1 yr-1**. If we apply a 20% buffer to this rate of sequestration (as is standard practice for certification schemes), Boothby could sequester 4.16tCO_2e ha-1 yr-1 for 20 years. This equates to a total of 44,096 tonnes of CO_2e, with a potential value of £3,307,200 or £312 ha-1 yr-1.

Whether this financial output translates to good value will depend on the existing business model under which a project operates. However, it is likely to be competitive with other land uses on some low-grade land.

This project's view is that prices do not yet reflect the true value of nature recovery and will need to rise substantially before natural capital revenues can meaningfully incentivise process-led nature restoration more widely.

07

Conclusion and next steps

Section 7:
Conclusion and next steps

7.1 Overview

This project has made an important contribution to understanding the carbon sequestration and storage potential of 'rewilding habitats' in lowland Britain. However, it has also highlighted the data gaps that still need to be plugged and the challenges associated with measurement of carbon sequestration and storage in dynamic habitat mosaics.

What is encouraging is the climate mitigation potential of process-led nature restoration. When combined with the proven biodiversity impact of such projects, a powerful case can be made to mainstream this land use as a nature-based solution to the twin environmental crises our societies face.

In this final section, we explore some more targeted recommendations for how process-led nature restoration can be more effectively integrated with emerging ecosystem markets, to enable the scaling of this land use.

7.1.1 Policy

Policymakers have an important role to play in terms of setting the agenda for land management in the UK. Clear, unequivocal support of process-led nature restoration as a land use is required, backing its role in helping the UK combat the climate and biodiversity crises. This will grant these activities legitimacy and encourage more land managers to deploy them on appropriate ground.

More specifically, in the context of emerging nature markets, a key role for policymakers is in market making, as with Biodiversity Net Gain, and / or market facilitation, as with the voluntary carbon market. Urgent consideration must be given to the demand side of voluntary markets to consider how this can be strengthened and facilitate the flows of capital that will be required for the UK Government to meet its nature recovery objectives.

Ultimately, this will mean having a roadmap for voluntary markets to transition into compliance markets over the coming decades and considering innovative blended finance approaches to fund nature recovery on the ground. [35]

7.1.2 Data and data acquisition

This project has highlighted the requirement for more robust datasets to underpin estimates of carbon sequestration and storage in 'rewilding habitats'. Equally important will be standardisation of the data acquisition methodologies and finding cost-effective technologies to undertake project MRV.

The recently published research from the University of Oxford [15] highlights that rewilding habitats have significant carbon sequestration potential and, crucially, over timeframes are relevant to net zero targets for 2050 or earlier.

Process-led nature restoration projects can therefore have good confidence that they will be providing significant climate mitigation, with further MRV likely to help build the breadth of datasets required and refine the technological and methodological approaches to data collection.

7.1.3 Finance

Carbon finance alone cannot fund lowland nature recovery at today's credit prices. The costs of delivery for process led nature restoration, as well as the required expertise, monitoring and ongoing management are not yet captured in the price of a carbon credit.

Carbon prices need to rise, other ecosystem services need to be priced into bundled offerings and further consideration needs to be given to the creation of new ecosystem markets if the private sector are to play a significant role in financing nature recovery. A London School of Economics (LSE) assessment concluded that, "it will be very hard to achieve net zero emissions in the UK without a proper price on carbon".[36] This project endorses that view and suggests the price for high-integrity, nature-based carbon credits needs to rise to £150 - £200 per tonne before carbon finance will start to be a feasible option for funding nature recovery. [36]

7.1.4 Next steps

The next steps for the collaboration of partners who pulled together this report is to;

- Disseminate the data gathered around soil carbon as part of this project, including the publication of a peer reviewed academic paper.
- Support and enable further studies and projects to produce similar sets of evidence, based on strong baselining and monitoring.
- Work with organisations such as Rewilding Britain to support market access and collaboration for rewilding projects.
- Publish progress made at Boothby Wildland as it continues to innovate and lead the way in funding nature recovery through the private sale of ecosystem services.

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